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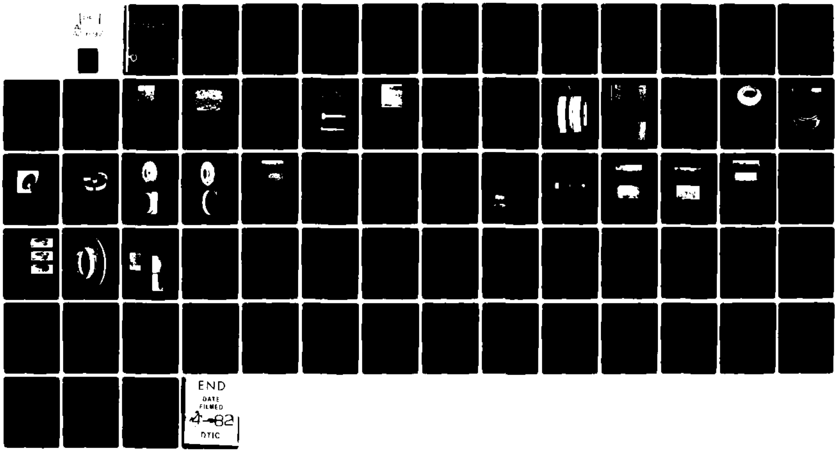

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MANUFACTURING METHODS AND TECHNOLOGY
(MANTECH) PROGRAM

CHEM-BRAZE ABRADABLE SEAL ATTACHMENT TO AIRCRAFT GAS TURBINE COMPRESSOR COMPONENTS

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FINAL REPORT

January 1982

Contract No. DAAG46-79-C-0102

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ABSTRACT

Manufacturing methods were established for bonding an abradable seal surface onto the stationary compressor element (e.g., case shroud) of small gas turbine engines utilizing an easily replaceable Chem-Braze bond system. Continuing work initiated under Army Contract DAAG46-78-C-0062, bonded specimens were prepared and evaluated in vibration and rub incursion tests. Tooling was fabricated for bonding a seal to Army supplied engine hardware, and NDI methods were established for inspecting bond integrity. Chemical stripping techniques for removing Chem-Braze attached seals were optimized to permit efficient refurbishment of severely worn seals. An economic analysis indicated significant cost savings for attaching abradable seals to compressor blade tip-shrouds using the improved Chem-Braze system compared to attachment with gold-nickel braze. The Chem-Braze system has been used successfully to bond abradable seals to titanium, cobalt, nickel and iron base alloys; however, attempts to use Chem-Braze to bond seals to selected aluminum and magnesium alloys were not successful.

PREFACE

This Final Report covers work performed under Army Contract DAAG46-79-C-0102 by United Technologies Corporation, Pratt & Whitney Aircraft Group, Government Products Division, West Palm Beach, Florida from October 1979 to September 1980.

This project was accomplished as part of the U. S. Army Aviation Research and Development Command Manufacturing Technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, equipment, and inspection methods for use in production of Army material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U. S. Army Aviation Research and Development Command, Attn: DRDAV-EGX, St. Louis, MO 63120.

This work was performed under the technical direction of Mr. Milton Levy of the Army Materials and Mechanics Research Center, Watertown, Massachusetts, and Mr. Fred Reed of the Army Aviation Research and Development Command, St. Louis, Missouri.

Mr. Stephen T. Narsavage, Program Manager for Pratt & Whitney Aircraft Group, Government Products Division, was responsible for the management and execution of the program. Appreciation is extended to Mr. Harold W. Pettit, Jr., P&WA responsible Materials Engineer, and Mr. Saed Safai, P&WA Senior Materials Engineer.

SUMMARY

An improved Chem-Braze system that incorporates glycerin as an inhibitor to prevent premature evaporation of the bonding composition was developed during the previous Army Contract, DAAG46-78-C-0062, and these results were reported in AVRADCOM Report No. TR 80-F-5. In the present program, manufacturing guidelines were modified to improve the Inhibited Chem-Braze (ICB) procedure for attaching FELTMETAL® seals to steel, titanium, and nickel-based alloys, and ICB bonding procedures were investigated for attaching seals to selected aluminum and magnesium alloys.

FELTMETAL attachment to high strength aluminum and magnesium alloys using established ICB procedures was attempted but resulted in strength degradation of the base metals. Several alternate methods for FELTMETAL seal attachment using modified cure cycles or substrate heat treatments were examined. One approach consisted of simultaneous curing of ICB cement during the heat treatment of the aluminum metal substrate. Although this method resulted in excellent FELTMETAL adhesion to high strength alloys, substrate warpage occurred.

Adhesion and structural integrity of established ICB attached FELTMETAL seals to steel, titanium, and nickel-based alloys was evaluated by vibration and rub rig testing. Visual and metallographic examinations showed no ICB degradation due to vibration or rub testing.

A quick and inexpensive chemical stripping technique developed during the previous contract was optimized for removing worn abradable seals attached with ICB cement. Process control parameters were selected, and metallography and tensile strength testing of the reworked seals revealed excellent reproducibility of the attachment process.

A cement thickness dispensing tool and expandable ring segments were used to attach seals to substrates. Feasibility of the tooling was demonstrated by attaching seals to simulator rings and engine hardware.

Nondestructive inspection (NDI) techniques were investigated to identify intentionally fabricated voids, disbonds, and delaminations in ICB joints. Three techniques were selected which fully characterized the various defects. Limitations of each method with respect to defect morphology and size were also evaluated.

An economic analysis demonstrated a significant potential cost saving for attaching abradable seals with the ICB bonding technique compared with the use of gold-nickel braze. Lower material costs, simpler attachment procedures, and lower tooling costs all contributed to the cost effectiveness of the ICB attachment system.

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SECTION I

INTRODUCTION

Pratt & Whitney Aircraft Group, Government Products Division (P&WA/GPD) of United Technologies Corporation routinely uses various types of seal attachment methods in the manufacture of gas turbine engine compressors. One system currently in use for blade-tip shroud sealing is metallurgically brazed in place FELTMETAL®, a sintered fiber abradable.

This system incorporates a gold-nickel braze attachment and has provided abradability, erosion resistance and reliability. Because of its advantages, it would be desirable to incorporate sintered abradables throughout the compressor for steel, titanium, nickel-based, or more recently developed light weight alloy shroud cases.

Although effective, the attachment of sintered abradables with metallurgical brazes is relatively expensive and not particularly suited for refurbishment. Removal of the abradable is accomplished by grinding and/or machining, which occasionally causes distortion of lightweight compressor case hardware.

Therefore, P&WA/GPD developed the Chem-Braze bonding system for attaching abradable sheet materials such as FELTMETAL to compressor case assemblies for blade tip-shroud sealing. The system has demonstrated its viability in preliminary engine tests. Attachment involves simple mechanical fixturing and curing, and removal is facilitated by chemical stripping. All operations are relatively fast and inexpensive.

High strength aluminum and magnesium alloys are being increasingly utilized in the compressor section of gas turbine engines for improved efficiency and material economics. However, new attachment techniques are required to bond FELTMETAL abradables to these alloys, because most brazing procedures are not compatible with aluminum and magnesium metallurgy.

Under a previous Army Contract, DAAG46-78-C-0062, Chem-Braze Abradable Seal Attachment, manufacturing guidelines were established for Chem-Braze bonding FELTMETAL seals to steel, titanium, and Ni-based alloys.

These activities were continued under Army Contract DAAG46-C-79-0102, Chem-Braze Abradable Seal Attachment. This program consisted of four phases: manufacturing guidelines for Chem-Brazing abradable seals to aluminum and magnesium alloys were investigated during Phase I. Evaluation of the physical characteristics of the Chem-Braze bond and optimization of stripping procedures were conducted during Phase II. The design and fabrication of tooling used to manufacture seal attachments and scale-up of inspection equipment to nondestructively evaluate Chem-Braze bonds were conducted during Phase III. During Phase IV, an economic analysis of the ICB seal attachment system was conducted.

SECTION II

TECHNICAL DISCUSSION

Prior experience with the Inhibited Chem-Braze (ICB) system demonstrated its feasibility and economic merit for attaching abradable gas path seals in gas turbine engines. Continuing work initiated under Contract Number DAAG 46-78-C-0062, the efficacy of using ICB (Appendix A) for attaching FELTMETAL® (Appendix B) seals to selected aluminum and magnesium alloys was investigated. Previously established manufacturing guidelines (Appendix C) served as the starting point for this effort.

Throughout Phases I, II, and III of this program ICB attachments to various alloys were investigated. These alloys are listed here and are more fully defined in Appendix D.

AMS 4117 Tempered Aluminum Alloy Bars and Rings
AMS 4115 Annealed Aluminum Alloy Bars and Rings
AMS 4025 Annealed Aluminum Alloy Sheet and Plate
AMS 4375 Annealed Magnesium Alloy Sheet and Plate
AMS 4911 Annealed Titanium Alloy Sheet, Ship and Plate
AMS 4928G Titanium Alloy Bars and Forgings
AMS 5398 Steel Coatings
AMS 5504 Steel Sheet, Strip and Plate
AMS 5536G Nickel Base Sheet and Plate
Mar-M509 Cobalt Base Alloy.

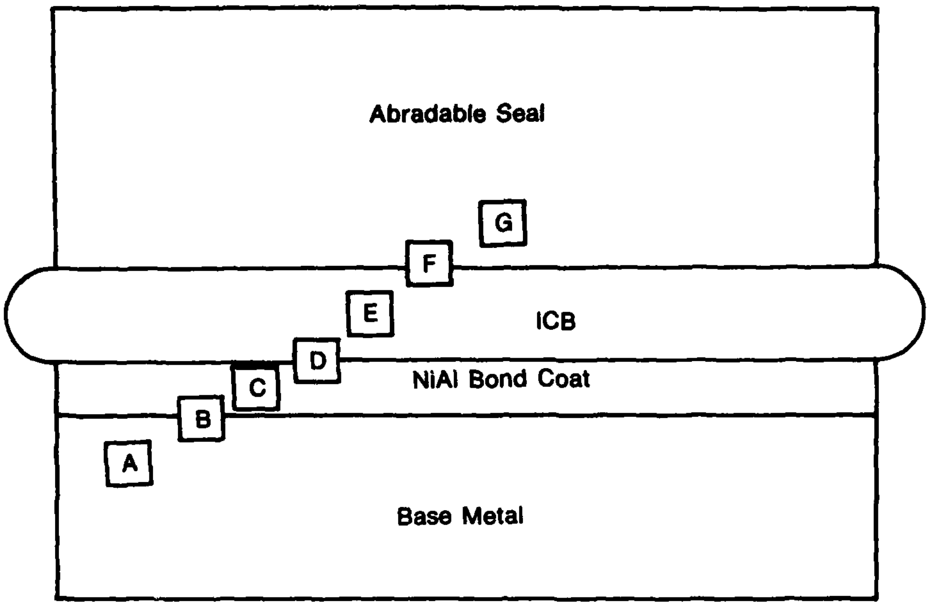
PHASE I — ALUMINUM AND MAGNESIUM SUBSTRATE ATTACHMENT INVESTIGATION

In this phase of the program, the efficacy of bonding FM 515B FELTMETAL seals to aluminum and magnesium substrates using ICB cement was investigated. This investigation was conducted by tensile testing bond bar samples which were prepared and tested per procedures described in Appendix E. Similar tests were conducted in the previous program using steel, titanium, and nickel-based metal substrates, with acceptable ICB attachments of FELTMETAL seals demonstrated after the proper manufacturing methods were established. Therefore the tensile strengths of ICB attachments to aluminum and magnesium substrates were compared to the tensile strengths of the ICB attachments to steel, titanium, and nickel-based alloys.

Task 1 — Attachment to AMS 4117 and AMS 4115 Aluminum Alloys

Using bonded abradable seals tensile strength testing determines the weakest location in the system. Figure 1 shows a schematic of the potential failure locations using this system. The previous program determined that tensile failures occurred cohesively within the FMS 515B abradable material at stresses from 445 to 730 psi when acceptable ICB attachments were fabricated. Failure within the abradable rather than other potential failure locations is desirable. This assures that the bond attachment is at least as strong as the abradable seal. Similar results are desirable for ICB attachments to any alloy.

Therefore, the tensile strength of ICB attachments to bondcoated aluminum substrate was determined. This was accomplished by attaching ICB to Metco-405 nickel aluminide (NiAl) bondcoated AMS 4117 (T-6) tempered aluminum bondbars following procedures which were established during the previous program (Appendix C except for a maximum cure temperature of 700°F, not 1000°F). Tensile testing was conducted as described in Appendix E. The lower cure temperature of 700°F was used with tempered aluminum bond bars in an attempt to fabricate a durable ICB bond without annealing the substrate.



A. Base Metal
B. Base Metal to Bond Coat Interface
C. NiAl Bond coat
D. Bond Coat to ICB Interface
E. ICB
F. ICB to Abradable Interface
G. Abradable Seal

FD 230760

Figure 1. Potential Failure Locations

Tensile test results listed in Table I demonstrate that tensile failures occurred adhesively at the bond coat to ICB interface for ICB attachment to AMS 4117 aluminum. This undesirable failure location indicates that the ICB bond is weaker than the abradable seal. Post-cure hardness measurements revealed that the AMS 4117 aluminum substrate annealed during the cement cure process. Previous experience demonstrated that sufficiently mature ICB bonds cannot be fabricated at ultimate cure temperatures below 700°F. Therefore, the approach of ICB bonding to tempered aluminum alloys was abandoned.

It was theorized that tempered aluminum (AMS 4117) lacked sufficient ductility to permit stress relaxation at the ICB to base metal interface during the cure cycle. Handbook physical properties, which are listed in Table 2, indicate that annealed aluminum (AMS 4115) is more ductile than tempered aluminum (AMS 4117).

ICB attachments to AMS 4115 aluminum bond bars were fabricated using previously established manufacturing guidelines (Appendix C). Bond bar samples were prepared and tensile testing indicated that acceptable ICB attachments had been achieved. The attachments were judged acceptable since tensile failures occurred cohesively within the FM 515B abradable. A typical cross section of FM 515B abradable seal ICB attached to AMS 4115 after ultimate tensile strength testing is shown in Figure 2.

TABLE 1. TENSILE FAILURE LOCATIONS

Substrate	Failure Location
AMS 4117 Aluminum	Bond Coat to ICB Interface
AMS 5613 Steel AMS 4928 Titanium AMS 5536 Nickel	Within FM 515B

TABLE 2. PHYSICAL PROPERTIES OF SELECTED MATERIALS

	Elongation,[1] *%*	*Hardness,*[1] *Bhn*	*Precipitation Heat Treat Temperature, °F*	*Coefficient of Expansion, α (µin./in./°F) at 1000°F*	*Tensile Strength, psi*	*Compressive Strength, psi*
AMS 4025	No distinction in property values between bar and sheet forms of the alloy					
AMS 4115	30	30	—	18.4	18,000[1]	—
AMS 4117	17	95	985 ± 10	18.4	45,000[1]	—
AMS 4375	15	56	—	20.0	37,000[1]	16,000[1]
AMS 4376	21	73	—	20.0	42,000[1]	26,000[1]
FM515B	—	—	—	9.2	445[2]	330[3]
ICB Cement	—	—	—	8.3	4,150[2]	4,200[3]

[1]Data was obtained from *Metals Handbook*, 8th ed., Vol 1, "Properties and Selection of Metals," Taylor Lyman, editor, and Howard E. Boyer, Managing Editor, et al., American Society for Metals, Metals Park, Ohio.
[2]Data obtained during this program.
[3]Data obtained from material suppliers.

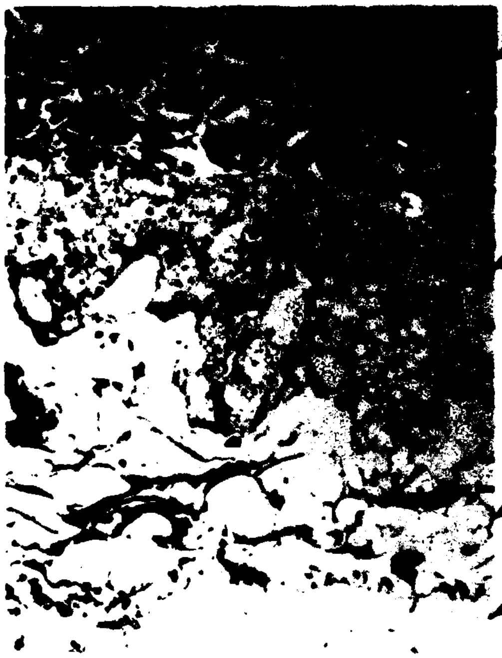


Figure 2. Inhibited Chem-Braze Seal Attachment to AMS 4115 Aluminum Substrate

Gas turbine engine compressor cases require the use of tempered aluminum alloys, therefore, FM 515B seals were ICB attached to thin-walled (0.063 in. thick), annealed AMS 4025 aluminum plate, which was used to simulate compressorcase construction, followed by an attempt to temper the aluminum substrate. This was accomplished by water quenching the ICB seal attachment/aluminum substrate assembly from ICB ultimate cure temperature (1000°F). This procedure produces a fully cured ICB attachment and T-4 tempers the aluminum. The solution heat treatment (T-4) is an intermediate step in processing fully aged T-6 aluminum. The ICB attachments, which were subjected to this processing, survived; however, the aluminum substrate showed excessive warping.

Other quenching techniques or fixturing techniques might prevent substrate warpage but this processing development was beyond the scope of this program which only addressed the ICB attachment to aluminum substrates using previously established ICB manufacturing procedures. Therefore, additional attempts to ICB bond to aluminum substrates were not pursued.

Task 2 — Attachment to AMS 4375 Magnesium Alloy

Difficulty in ICB bonding to hardened magnesium was anticipated since hardened AMS 4376 magnesium has similar physical characteristics to tempered AMS 4117 aluminum (Table 2). The selected approach was to ICB bond FM 515B seals to annealed magnesium and subsequently harden the magnesium substrate.

The FM 515B seals were ICB attached to annealed AMS 4375 magnesium bond bars using previously established processing guidelines (Appendix C) except for a lower ultimate cure temperature. These samples were cured at 700°F, instead of 1000°F, since magnesium alloys will ignite in air at temperatures in excess of 750°F. The bond bars were tensile tested as defined in Appendix E.

The tensile tested samples demonstrated acceptable ICB attachments since failures occurred cohesively within the FM 515B abradable seal. A typical cross section of an ICB seal attachment to AMS 4375 after tensile strength testing is shown in Figure 3.

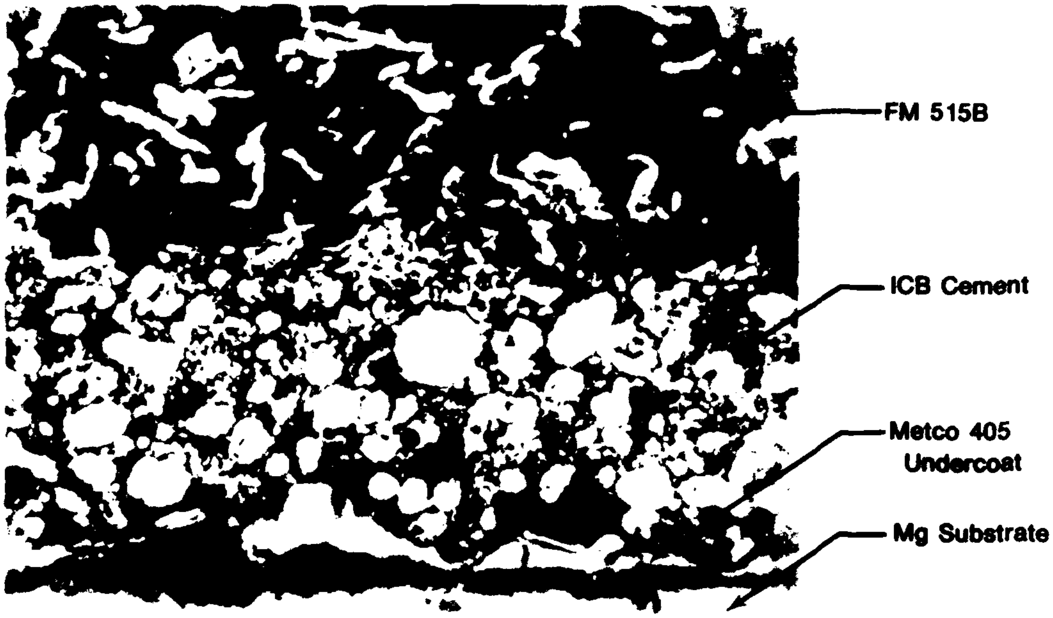


Figure 3. Attachment to AMS 4375 Magnesium Substrate

The AMS 4375 magnesium is a work hardening alloy. Attempts to work harden substrates with ICB seal attachments in place were conducted by applying compressive loads. The strain required to work harden the alloy exceeded the ultimate compressive strengths of ICB and FM 515B.

Other thermally hardenable magnesium alloys exist which utilize relatively slow air quenches during the thermal hardening process. Examples of these alloys are listed in Table 3 and offer potential for use with ICB seal attachments.

Since successful ICB seal attachments were not achieved with the selected aluminum and magnesium alloys, activities during Phases II and III utilized steel, titanium, and nickel-based substrates.

PHASE II — PHYSICAL CHARACTERISTICS AND CHEMICAL STRIPPING OPTIMIZATION

The effort under Phase II consisted of assessing the efficiency of ICB seal attachments via two types of dynamic rig testing. A chemical stripping technique which removes ICB attached worn abradable seals, thereby permitting refurbishment, was also optimized during Phase II.

TABLE 3. Mg ALLOYS WITH HEAT TREATMENTS COMPATIBLE WITH ICB CEMENT CURE PROCEDURES[1]

Wrought Alloys		*Solution Heat Treatment Temp., °F*	*Time at Temp., hr*
AM 100		775	18
AZ 80		750	2-4
HM 21		750	1
HM 31		*850	1
ZK 60		925-935	
HK 31A		*750	1
Casting Alloys			
AZ 63A		720-730	12
AZ 91		770-780	18
AZ 92	(Preheat 500°F)	760-770	18
ZK 61		930	5

[1]Information gathered from *Metals Handbook*, Vol. 1.
*Full anneal step for 0 condition metal
Note: Exposing Mg alloys to temperatures above 750°F cause Mg fires unless inert atmospheres are provided in the furnace while attaching abradable seals.

Task 1 — Dynamic Rig Testing

Fatigue strength and rub abradability tests were conducted to determine the integrity of ICB attachments.

Subtask 1.1 Fatigue Strength Rig Tests

Gas turbine engine compressor cases are known to experience trinodal vibration modes during service. This translates to second bending mode vibrations of flat plate geometries.

FM 515B abradable seals were attached to AMS 5504 steel, AMS 4911 titanium, and AMS 5536 nickel-based substrates using ICB bonding parameters which are defined in Appendix C. The assembled samples were subjected to second bending mode vibration tests such that sinusoidal harmonic vibrations were induced. Test sample geometry and vibration test techniques are described in Appendix F. The tests were terminated at the first visible signs of seal system degradation which was accompanied by a drop in resonant vibration frequency. The number of cycles before failure occurred was measured.

All failures occurred within the FM 515B seals with cracking initiated at the point of maximum stress and propagating rapidly. In no case did ICB failure occur, thus the abradable seals remained attached. Second bending mode vibration test results are shown in Figure 4. These results demonstrate that fatigue failures were essentially unaffected by the type of substrate to which FM 515B was ICB bonded.

A planar view of an ICB bonded FM 515B seal before and after being fatigue tested is shown in Figure 5. The post vibration test sample contains a fatigue induced crack within the seal. A number of similar post vibration tested samples were metallographically analyzed to determine if cracking extended into the ICB. The analyses showed that the cracks did not extend into the ICB bond areas. The cross section of a typical ICB seal attachment after being fatigue tested is shown in Figure 6.

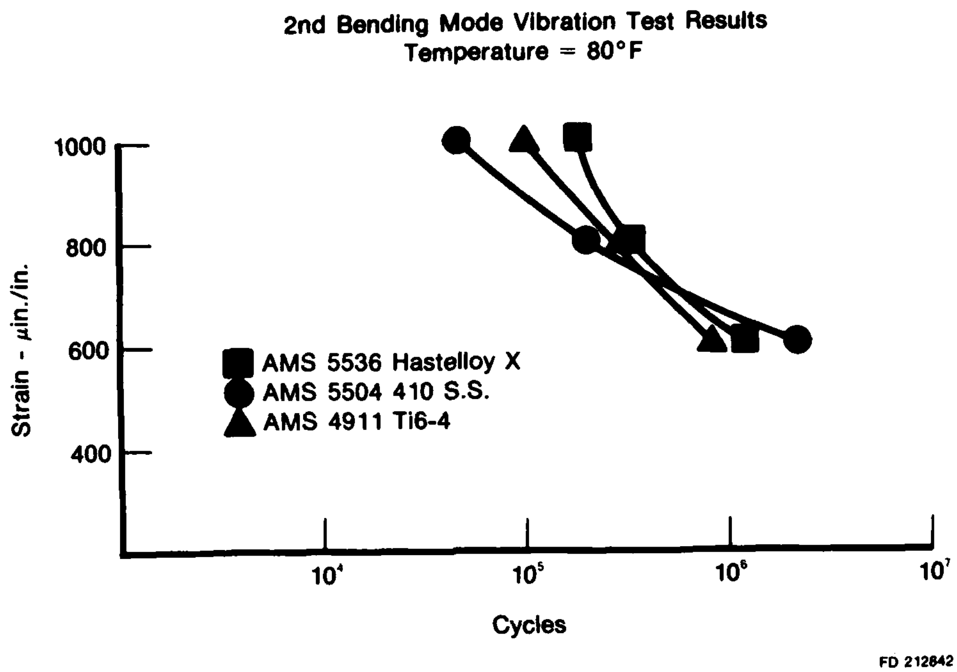


Figure 4. Fatigue Test Results

Mag: ½X Before FAL 59673

Mag: ½X After FAL 61606

FD 212841

Figure 5. Inhibited Chem-Braze Attached Seals Before and After Fatigue Testing

Figure 6. Fatigue Failure Zone in Abradable

Since failures initially occurred within the abradable seal and did not propagate into the bond areas, ICB attachments were judged acceptable in a second bending mode vibration environment.

Observations of the specimens during fatigue testing revealed that cracking originated at the edge of FM 515B seals and propagated through the fibrous pads. Additional fatigue test samples were prepared as before plus an application of 0.040 to 0.060 in. thick ICB coating to the edges of the FM 515B seals. The modified samples were also vibration tested in the second bending mode. The results of these tests are shown in Figure 7 and are compared to the previous results. Figure 7 shows a significant improvement in FM 515B fatigue durability attributable to the addition of ICB at the seal edges. This observation suggessts that ICB applied to the edges of FM 515B seals can enhance the fatigue life of this abradable material without detrimentally affecting its abradability.

Subtask 1.2 — Rub Abradability Rig Testing

Seal attachment efficiency was also determined by rub abradability testing ICB attached FELTMETAL seals. The single blade tip-seal rub-interactions were conducted under simulated engine conditions.

The FM 1109 (40% dense 347 stainless steel) abradable seals were attached to rub rig shoes using ICB bonding parameters as defined in Appendix C. The FM 1109 abradable seals are more difficult to abrade than FM 515B. Therefore, this abradable was selected for rub interaction testing to subject the ICB attachment to larger stresses than interactions involving FM 515B seals.

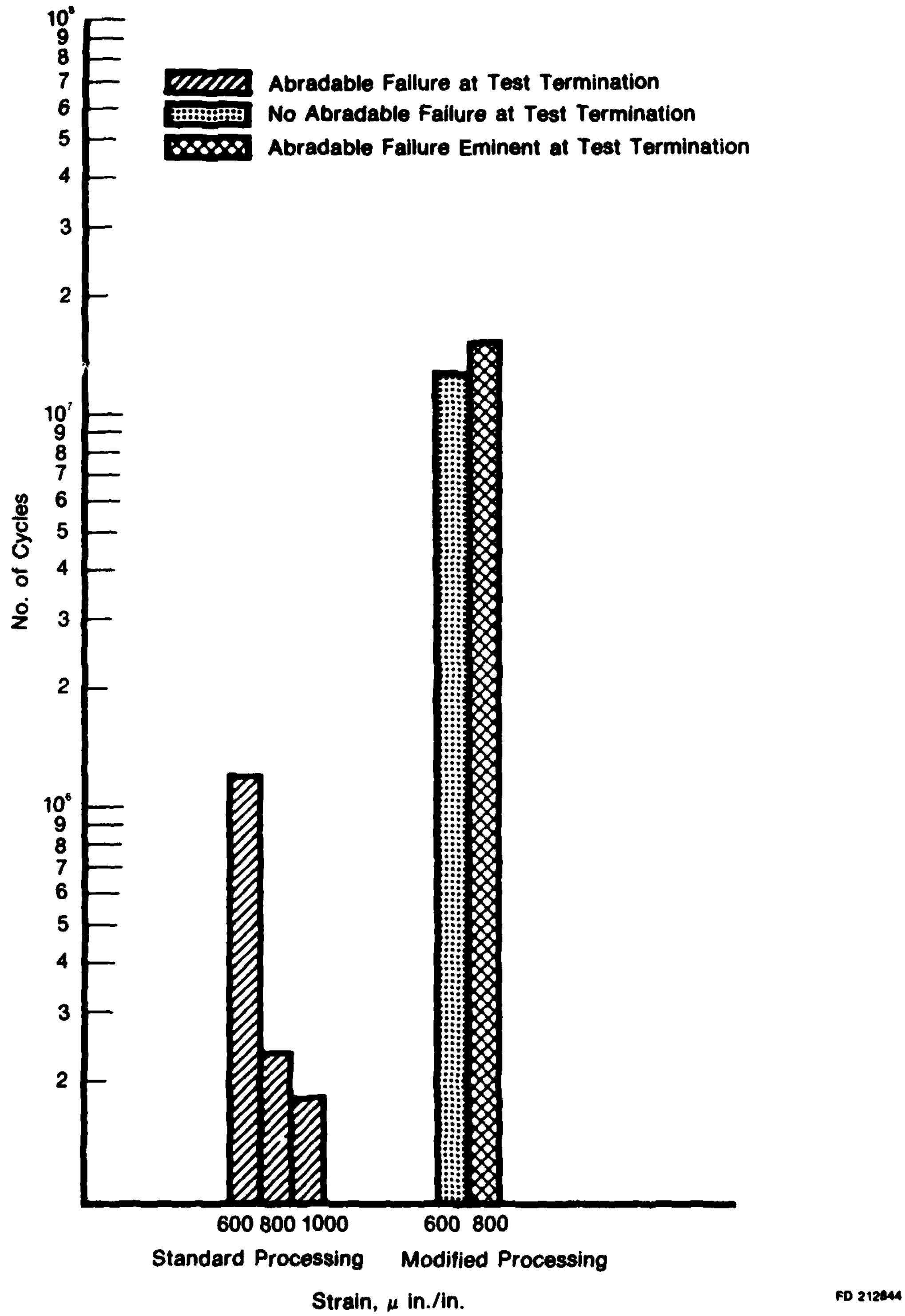


Figure 7. Fatigue Strength Comparison

The rub rig shoes with ICB attached seals were dynamically rub abradability tested. Visual observations of the post rub abradability tested samples are listed in Table 4 and indicated that all ICB seal attachments remained intact. A typical rub shoe assembly before and after rub rig testing is shown in Figure 8. Post-rub abradability test metallography also demonstrated that ICB seal attachments remained intact. Typical cross-sections of a rub abradability tested sample are shown in Figure 9.

TABLE 4. SEAL ATTACHMENT RUB TEST RESULTS

Test	*Plunge, in.*	*Results*
TI-33	0.010	Attachment remained intact
TI-34	[illegible]	Attachment remained intact
[illegible]	[illegible]	Attachment remained intact
[illegible]	0.015	Attachment remained intact
[illegible]	0.005	Attachment remained intact
TI-42	0.010	Attachment remained intact
TI-43	0.020	Attachment remained intact; blade failed

Task 2 — Refurbishment Optimization

Refurbishment of worn abradable seals that are ICB attached requires a technique to remove the initial seal attachment. Continuing efforts which were initiated under the previous program, a series of chemical stripping techniques were investigated.

The FM 515B seals were ICB bonded to AMS 5504 steel, AMS 4911 titanium, AMS 5536 nickel and Mar-M509 cobalt-based alloy flat plate samples. The ICB bonding parameters are defined in Appendix C.

The test samples were immersed in concentrated aqueous sodium hydroxide (NaOH) or aqueous potassium hydroxide (KOH) solutions at elevated temperatures. Solution temperatures, concentrations, and immersion times were varied. The time required for sufficient chemical reaction with the ICB to take place permitting the seals to be removed with hand pressure is shown in Figure 10.

Immersion in 5.0 to 6.0 lb/gal aqueous NaOH at 160 to 180°F for 2.5 to 3.0 hr are the preferred stripping parameters. The NaOH was selected over KOH because the NaOH immersion technique is a one step operation, whereas, immersion in aqueous KOH left ICB residues on substrates which required wire brushing for complete removal. High temperature (200°F) stripping baths are not as economical as 160 to 180°F baths due to energy related costs.

Metallographic analysis revealed that the selected aqueous NaOH stripping technique did not cause intergranular or surface attack of the alloys investigated. During the previous program, it was demonstrated that ICB attached seals which were refurbished using the selected approach remained as strong as the initial ICB seal attachment.

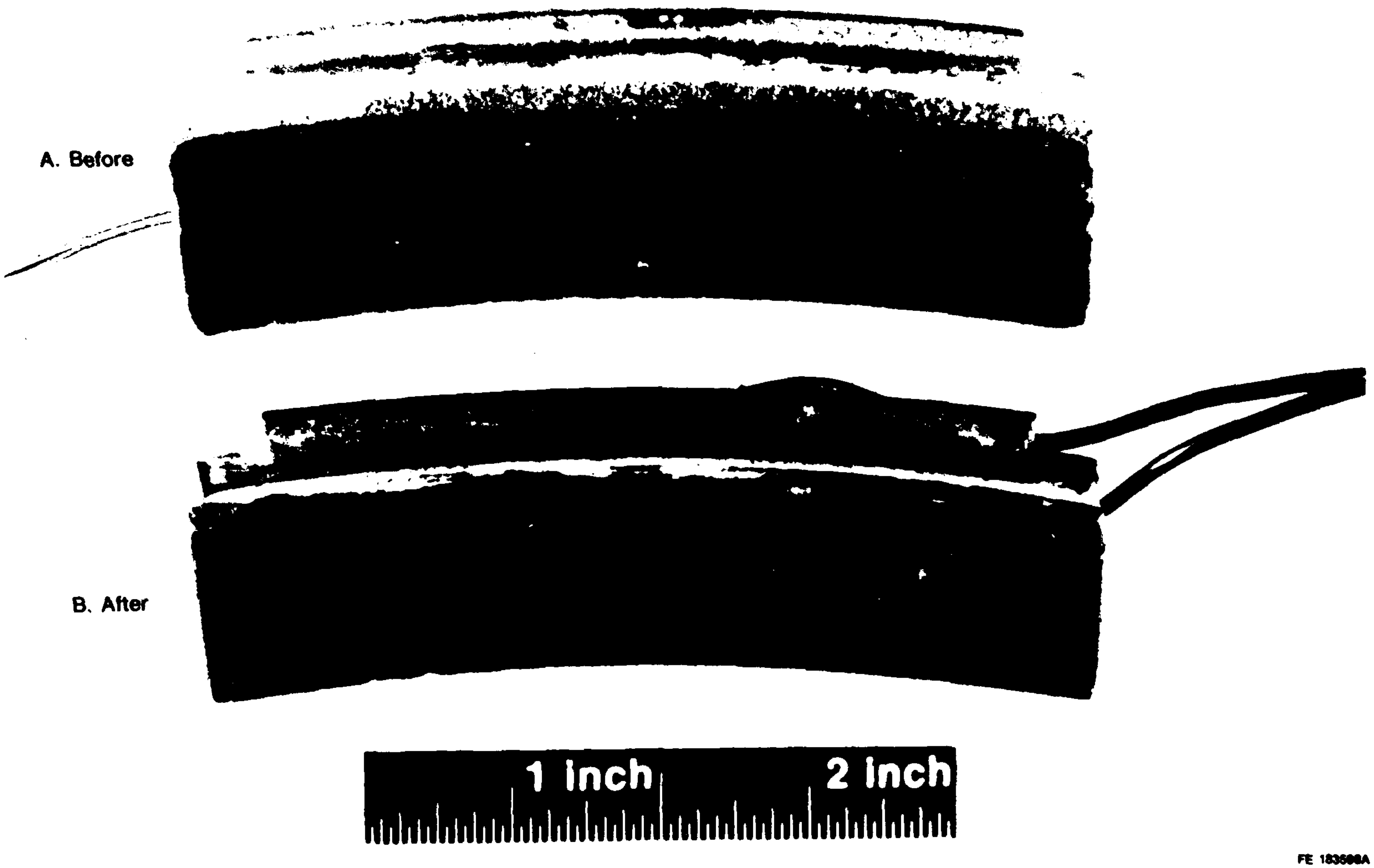


Figure 8. ICB Attached Seals Before and After Rub Abradability Rig Testing

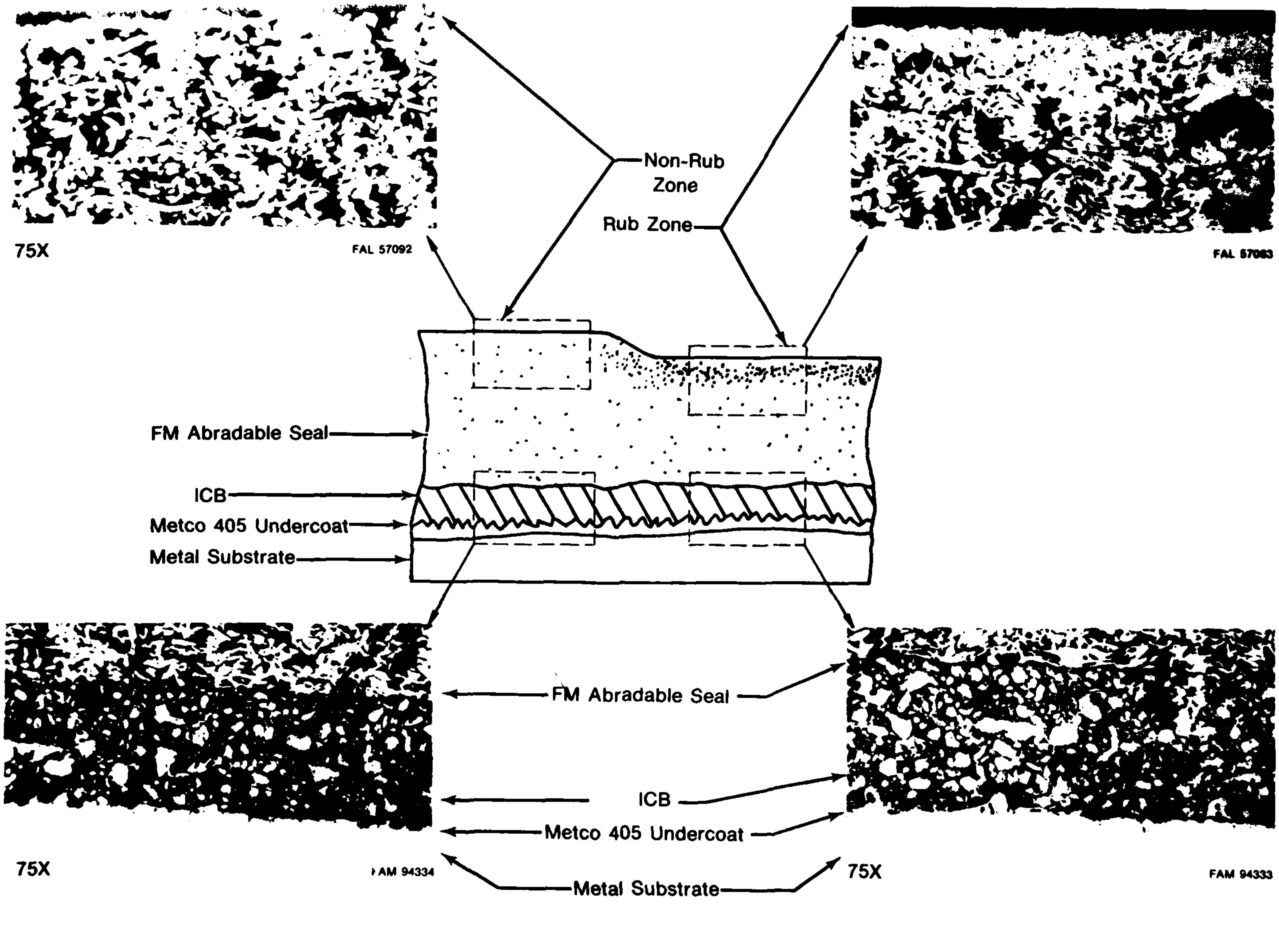


Figure 9. Seal and Seal Attachment Rub Results

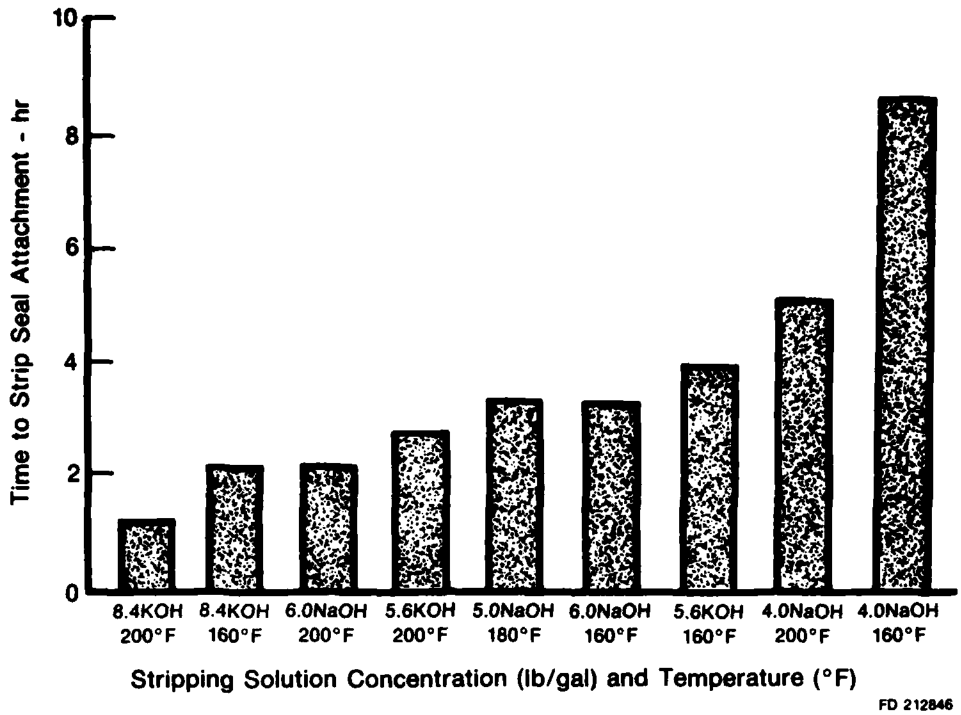


Figure 10. Chemical Stripping Optimization Results

PHASE III — MANUFACTURING METHOD DEMONSTRATION AND NONDESTRUCTIVE INSPECTION

During Phase III, tooling which is used during the ICB bonding process was fabricated and used in a number of attachment demonstrations. Nondestructive inspection (NDI) techniques were also established and utilized to inspect ICB seal attachments.

Task 1 — Tooling and Attachment Demonstrations

Under this task, a demonstration, which involved ICB attachment of FM 515B to the seal land of an Allison T-63 Front Diffuser Assembly, was conducted. The 17-4 PH stainless steel (AMS 5398 Appendix D) Front Diffuser Assembly as supplied by the Army is shown in Figure 11. The relationship of the seal land to the knife-edge assembly seal is shown schematically in Figure 12. Additional demonstrations involved ICB attachment to metal rings which duplicated the geometry of the engine hardware seal land. The ring attachment demonstrations permitted destructive analyses and provided an adequate number of samples for NDI and refurbishment demonstration.

The feasibility of two basic tools which are utilized during the ICB bonding operation was established during the previous program. These tools are used to control ICB thickness as applied to substrates and to exert pressure during a portion of the bonding operation.

The FM 515B material was contoured to fit engine hardware seal land and ring geometries. This was accomplished by subjecting the FM 515B to a series of rolling operations. Contoured seal segments were subsequently cut to length with mitered joints using simple fixturing and a jeweler saw. Seal segments prepared as described above are shown in Figure 13. In lieu of these operations preformed segments can be procured from the FM 515B manufacturer.

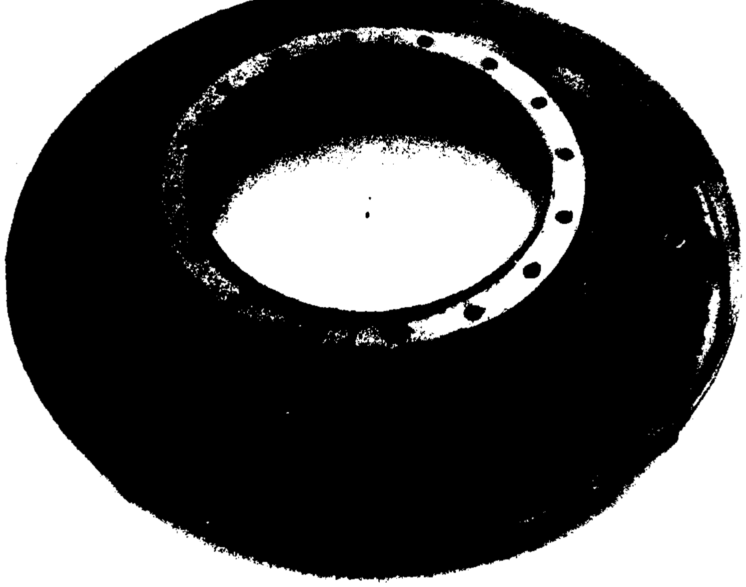


Figure 11. Allison T-63 Front Diffuser Assembly

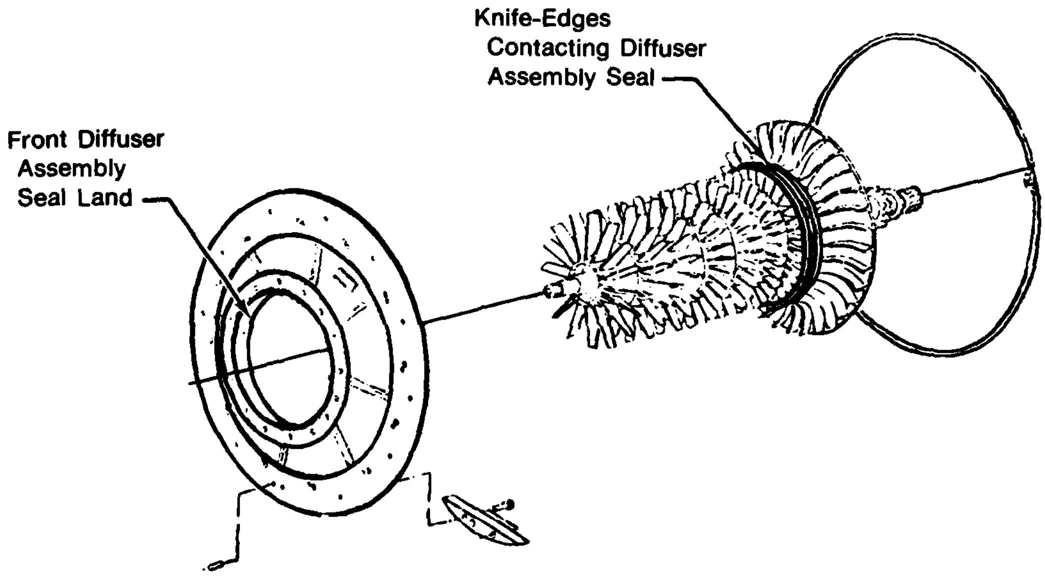


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Figure 12. Allison T-63 Knife-Edge Sealing Configuration

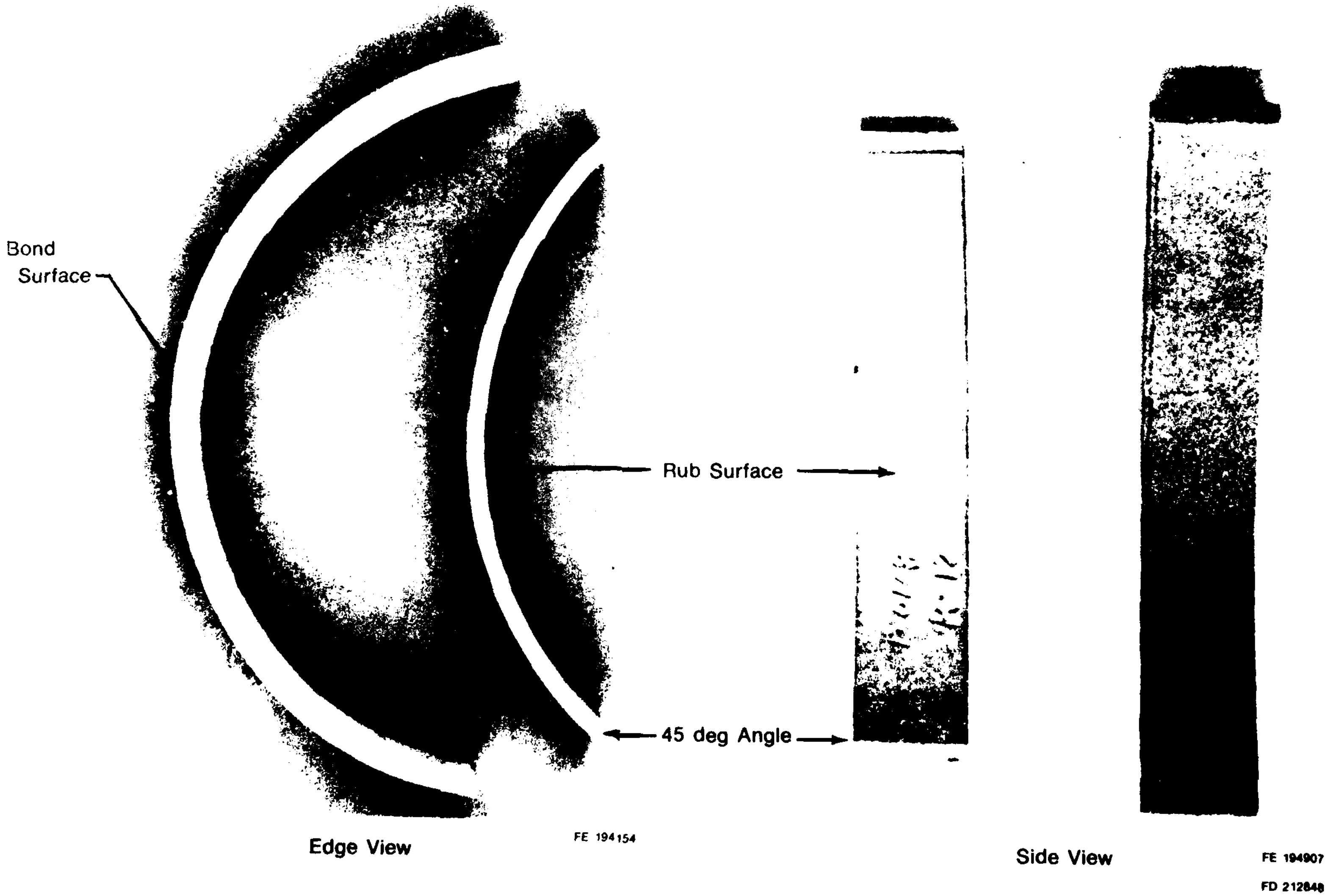


Figure 13. Side and Edge View of FELTMETAL® Segment

Metco 405 nickel aluminum was flame sprayed 0.003- to 0.005-in. thick on engine hardware and rings. The undercoat was sprayed using a Metco 4E wire gun and Metco's recommended spray parameters. An ICB bonding composition was prepared as described in Appendix A.

Then ICB was applied to the undercoated engine hardware and rings using a hand held tool (doctor blade) which skives a 0.008 to 0.012 in. thick layer. The ICB cement thickness tool was fabricated using Emerson and Cuming, Inc. CPC-19 urethane rubber and is shown in Figure 14.

Figure 14. Cement Thickness Control Tooling

Expandable ring segments which are shown in Figure 15 were fabricated to conform to engine hardware and ring seal lands allowing for space occupied by the abradable seals. Dimensions of the expandable ring segment tools are shown in Appendix G. The FM 515B seal segments were located on the seal lands which were previously coated with ICB. The expandable ring segments were located as shown in Figure 16 and used to apply bonding pressure. During the previous program, it was demonstrated that a uniform 200 psi pressure is exerted radially by controlling the force exerted on the peg portion of the expandable ring segment tooling. These assemblies were then dried and cured as described in Appendix C. This procedure was used to ICB bond FM 515B seals to 10 rings (4-AMS 5504 steel, 3-AMS 4911 titanium, and 3-AMS 5536 nickel rings) and the engine hardware. Figure 17 shows ICB seal attachments for a typical ring and the engine hardware.

Three rings (each base metal) with ICB bonded seals were sectioned to metallographically inspect the attachments. All three ring attachments exhibited well adhered bonds which were free of delaminations or excessive voids. A typical cross section of an ICB seal attachment to a ring is shown in Figure 18.

One AMS 5504 steel ring with an ICB attached seal was refurbished by immersion in aqueous NaOH using the stripping parameters which were previously described. Replacement FM 515B seals were applied to the ring by repeating the manufacturing sequence. The attachment was visibly inspected and demonstrated the viability of the refurbishment process for engine size hardware.

The remaining ring assemblies and the engine hardware assembly were saved for subsequent NDI evaluations.

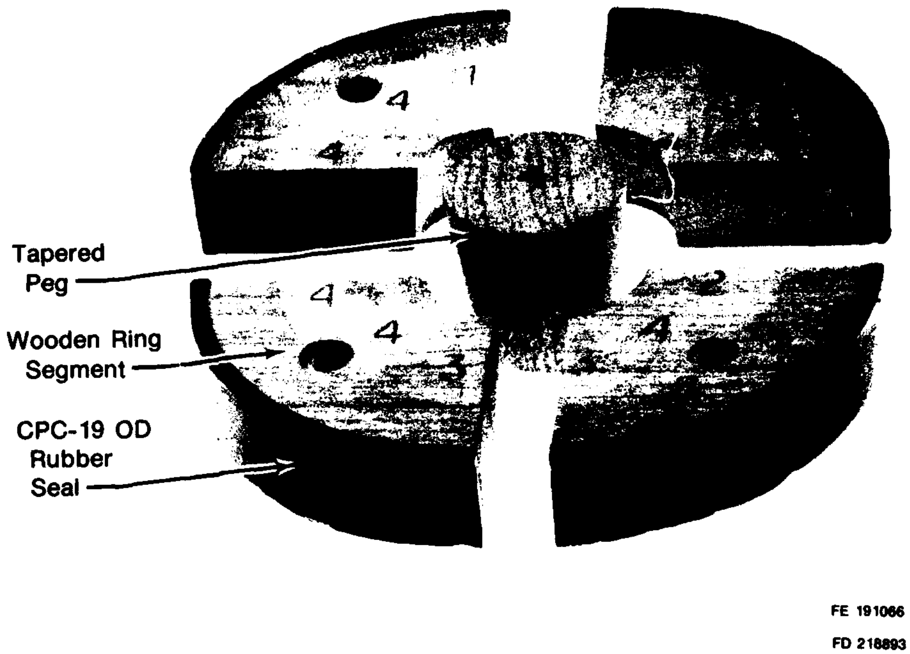


Figure 15. Expandable Ring Segments

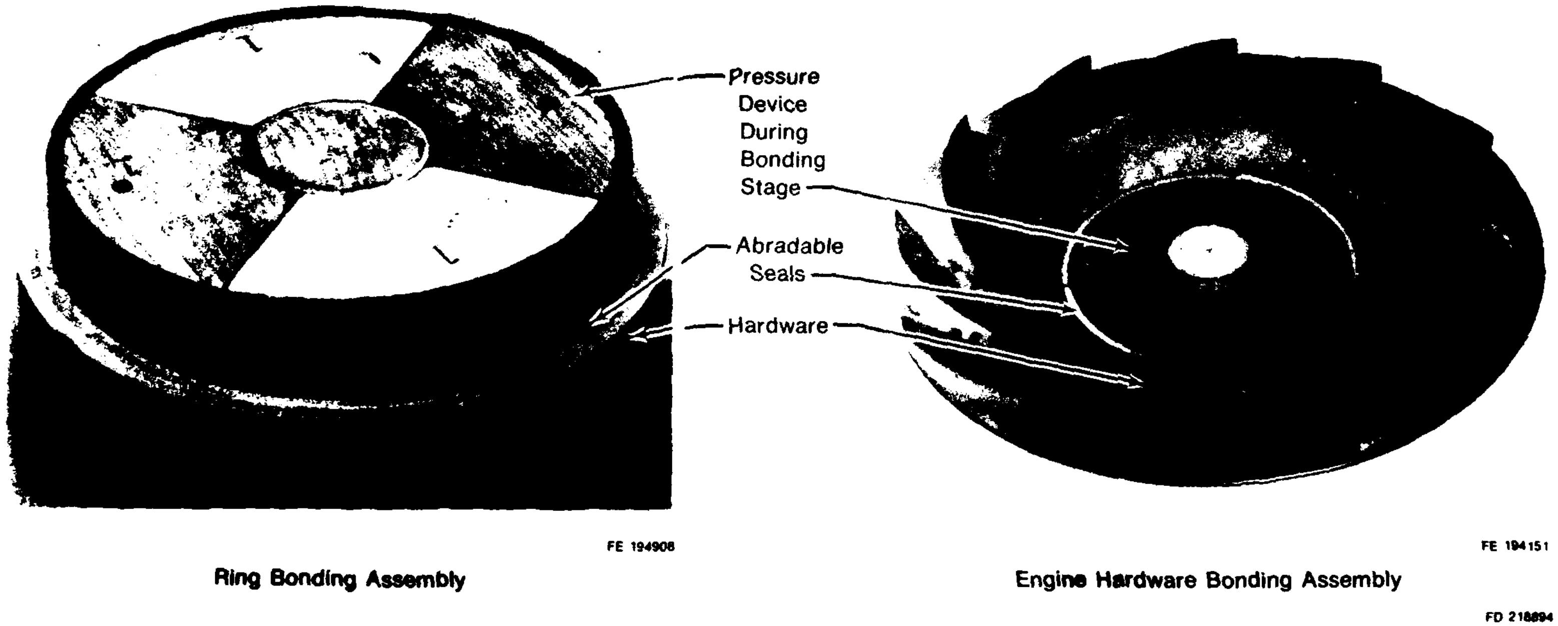
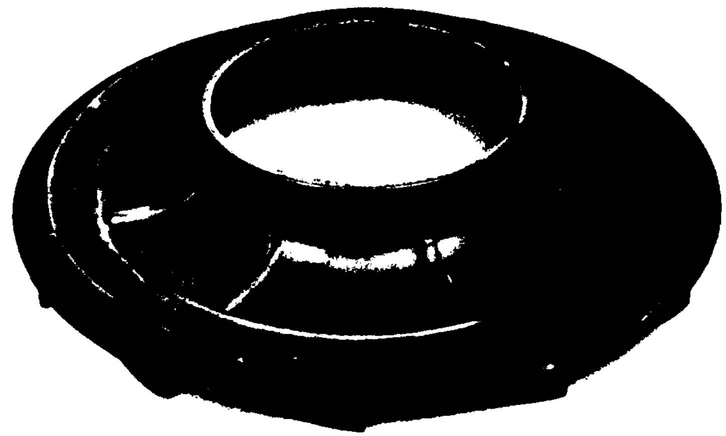


Figure 16. Inhibited Chem-Braze Bonding Assemblies

FE 194901

Ring



FE 194155

Engine Hardware

FD 218895

Figure 17. Inhibited Chem-Braze Seal Attachments

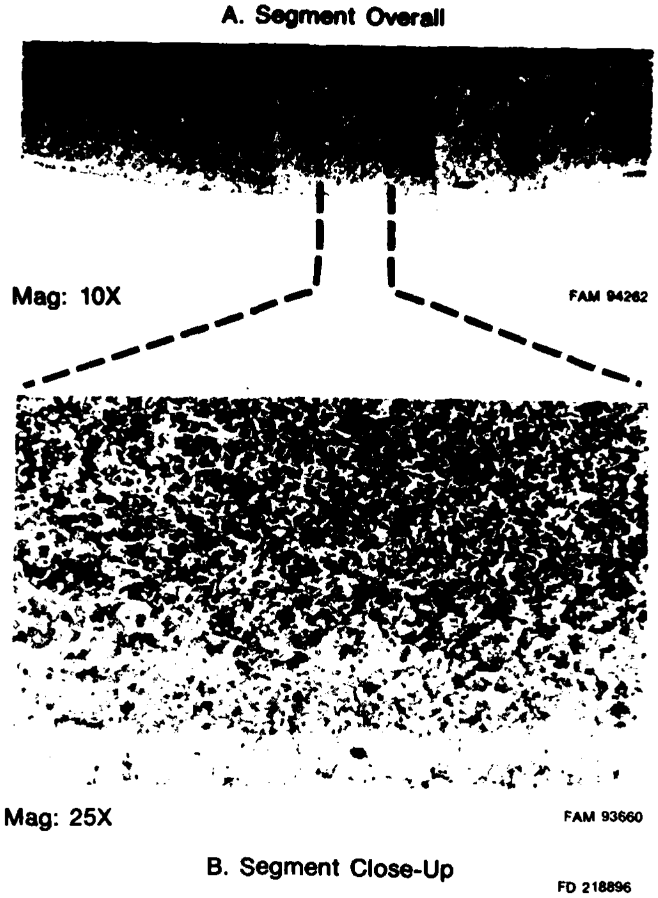


Figure 18. Ring Seal Attachment Metallography

Task 2 — NDI Technique

Four NDI techniques were investigated to determine their usefulness in detecting potential ICB bond defects. These techniques were selected on the basis of experience gained in other related programs. Each of the techniques is described below.

Ultrasonic inspection techniques have long been utilized for evaluating bonding integrity of abradable seal systems. In this program a pulse-echo ultrasonic technique which detects excessive echoing of transmitted signals from defect locations was utilized. A schematic of the pulse echo-ultrasonic NDI equipment is shown in Figure 19. An Automation Industries transducer (0.375-in. dia) transmitted a pulsed 2.25 MHz signal through water to a target (ICB bonded seals). Echoes from the target were received by a Mark III ultrasonic detector at a gain setting of 352. The detector was connected to a recorder. Rotation of the target and recorder was synchronized by a belt drive system. Recorder scans identified bond defects as blank spaces on the recorded image.

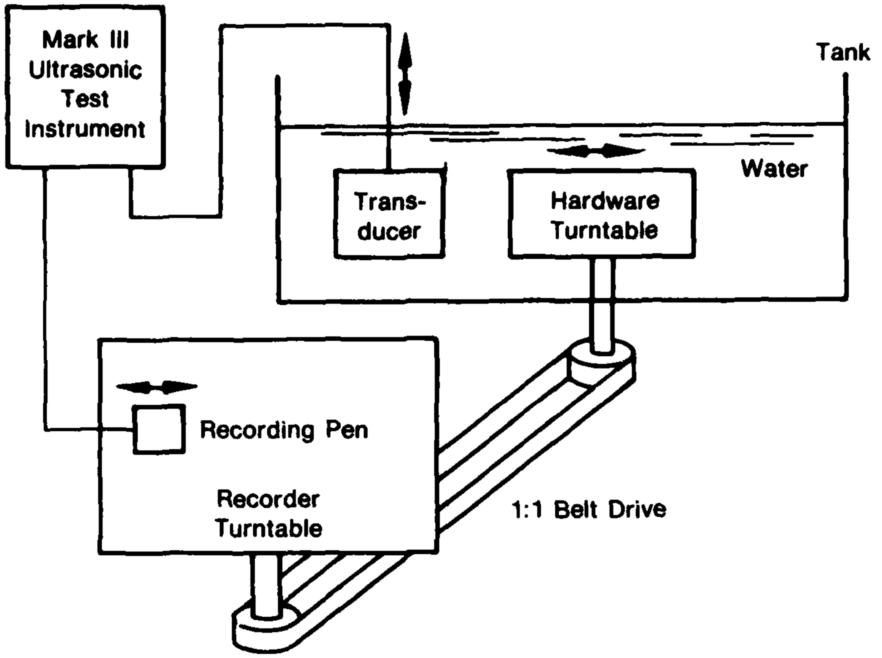


Figure 19. Pulse-Echo Ultrasonic Schematic

A laser holographic technique which combines time-average holographic images of both randomly and sinusoidally excited targets was investigated. A schematic of this equipment is shown in Figure 20. This technique utilizes a piezoelectric shaker to excite the test target. An argon laser was simultaneously focused on the target and holographic plates via an optical system. The piezoelectric generator was adjusted to emit broad band white noise followed by a sinusoidal frequency to more clearly define defects. Laser amplitude was adjusted to produce holograms of sharp contrast. Holograms were visible on the emulsified glass plates with defects appearing as dark or banded regions. Permanent records of the holograms are made by photographing the images.

Acoustic emission is a widely used inspection technique which detects stress waves emitted by a material undergoing irreversible deformations such as microcracking, phase transformation or plastic deformation under external stress. A schematic of the acoustic emission equipment utilized in this program is shown in Figure 21. The test procedure consisted of ICB bonding a FM 515B seal to a flat plate. A bond bar was subsequently attached to the abradable using a high strength epoxy. A 140 KHz resonant transducer was also attached to the abradable with methylcyanacrylate adhesive adjacent to the bond bar. A tensile load was applied to the bond bar and acoustic signals were amplified and monitored. At system settings of 60 dB gain, 35 dB amplitude threshold level, and a 1 sec reset for count rate monitor, it was determined that once the count rate reached 50 counts/sec consistently,

approximately 50% of the abradable's ultimate tensile strength had been reached at the load level attained. Predicted tensile strength was then calculated based on the tensile load indicated by the acoustic emission technique and the surface area of the attached bond bar as shown by:

$$S_{tensile} \qquad \frac{L}{0.50\ (A_{surface})}$$

Where:

S = Adhesion strength, psi

L = Tensile load indicated by acoustic emission as 50% of abradable strength, lb

$A_{surface}$ = Surface area of seal contacted by bond bar, in.^{2}

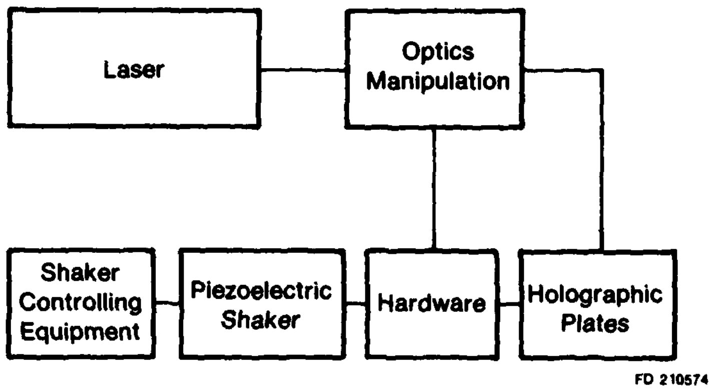


Figure 20. Laser Holography Schematic

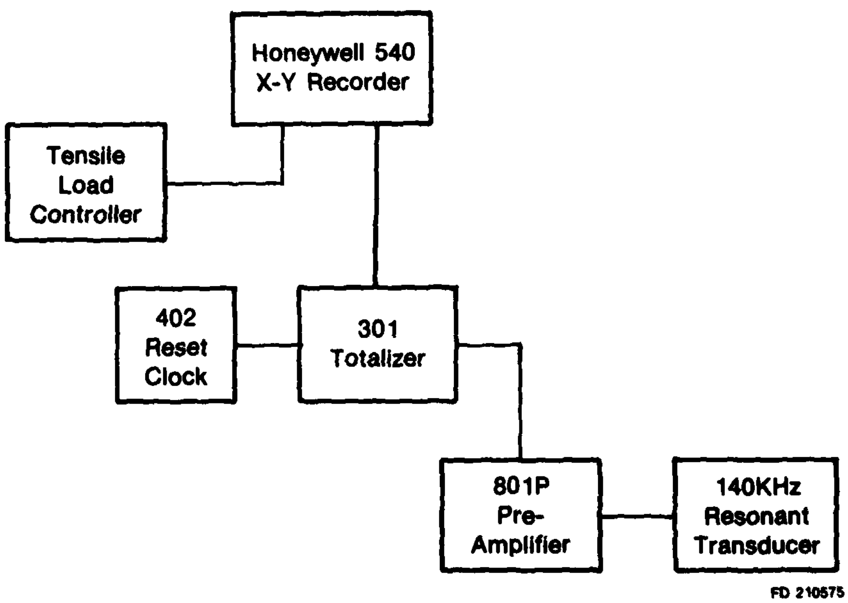


Figure 21. Acoustic Emission Tensile Strength Schematic

NDI samples were prepared by ICB bonding FM 515B to AMS 5504 steel, AMS 4911 titanium, and AMS 5536 flat plates. These samples were prepared with intentional defects at three possible locations. The defects were fabricated by spraying mating surfaces with a fluoropolymer during the ICB bonding procedure. Defects were categorized as disbonds, delaminations and voids which are defined in Table 5.

TABLE 5. NDI TEST SAMPLE DEFECT MORPHOLOGY

Type of Defect	*Location of Defect*
Disbond	Between metal substrate and ICB
Delamination	Between abradable seal and ICB
Void	Between layers of ICB

The flat plate NDI samples were inspected using each of the three previously mentioned techniques and X-ray radiography. It was determined that the X-ray radiographic technique was not capable of identifying ICB defects due to wash-out of the radiation passing through metal substrates. The radiation intensity required to penetrate metal substrates was too strong to reveal defects within the ICB.

The results of pulse-echo ultrasonic, laser holography and acoustic emission NDI evaluations were compared to destructive analyses. As shown in Figure 22, reasonable agreement between destructive and nondestructive inspection was achieved with each of the NDI techniques investigated. Therefore, the use of all three NDI techniques was extended to engine size hardware.

Rings with ICB seal attachments which contained intentionally fabricated defects were used to further determine the capability of each of the NDI techniques. Destructive metallography was performed on each of the rings for correlation with the NDI results.

Pulse-echo ultrasonic inspection was applied to selected rings. It was determined that the substrate material or seal geometry had no apparent effect on the ultrasonic technique's capability for locating defects. The technique located defects as small as 0.15 in. in diameter. Figure 23a shows NDI results for three different substrates. Destructive metallography revealed that the defect shown in Figure 23.a.1 is a 0.255 in. disbond (Figure 24). Destructive metallography also revealed that the defect shown in Figure 23.a.3 is a 0.33 in. void (Figure 25). The pulse-echo ultrasonic technique did not identify a defect in the titanium ring sample as shown in Figure 23.a.2; however, destructive metallography revealed that the sample contained a delamination as shown in Figure 26.

Laser holography was applied to the same rings which were previously inspected by the ultrasonic technique (Figure 23.b). It was determined that the substrate material or the seal geometry had no effect on the technique's capability for detecting defects. The holography technique did not identify a defect in the steel ring sample. However, holography identified a delamination in the titanium sample (Figure 23.b.2). Destructive metallography verified the presence of a delamination as previously shown in Figure 26. The metallographically prepared sample was inadvertently sectioned through this defect. Therefore, the actual defect was larger than shown in Figure 26. The nickel ring sample contained a disbond/void defect which was identified by laser holography (Figure 23.b.3). Destructive metallography (Figure 25) verified the presence of a 0.33-in. void.

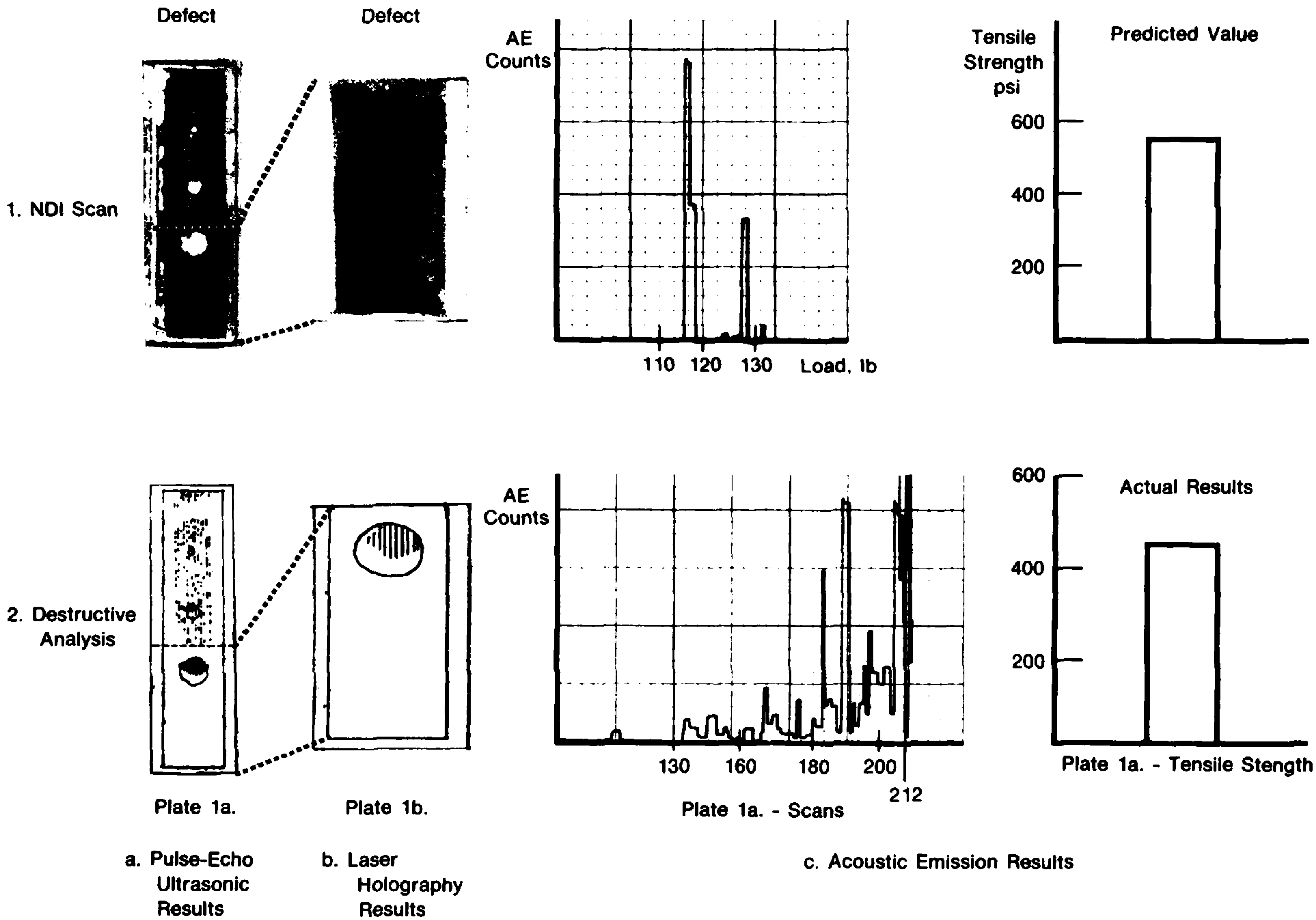


Figure 22. Nondestructive Inspection Results

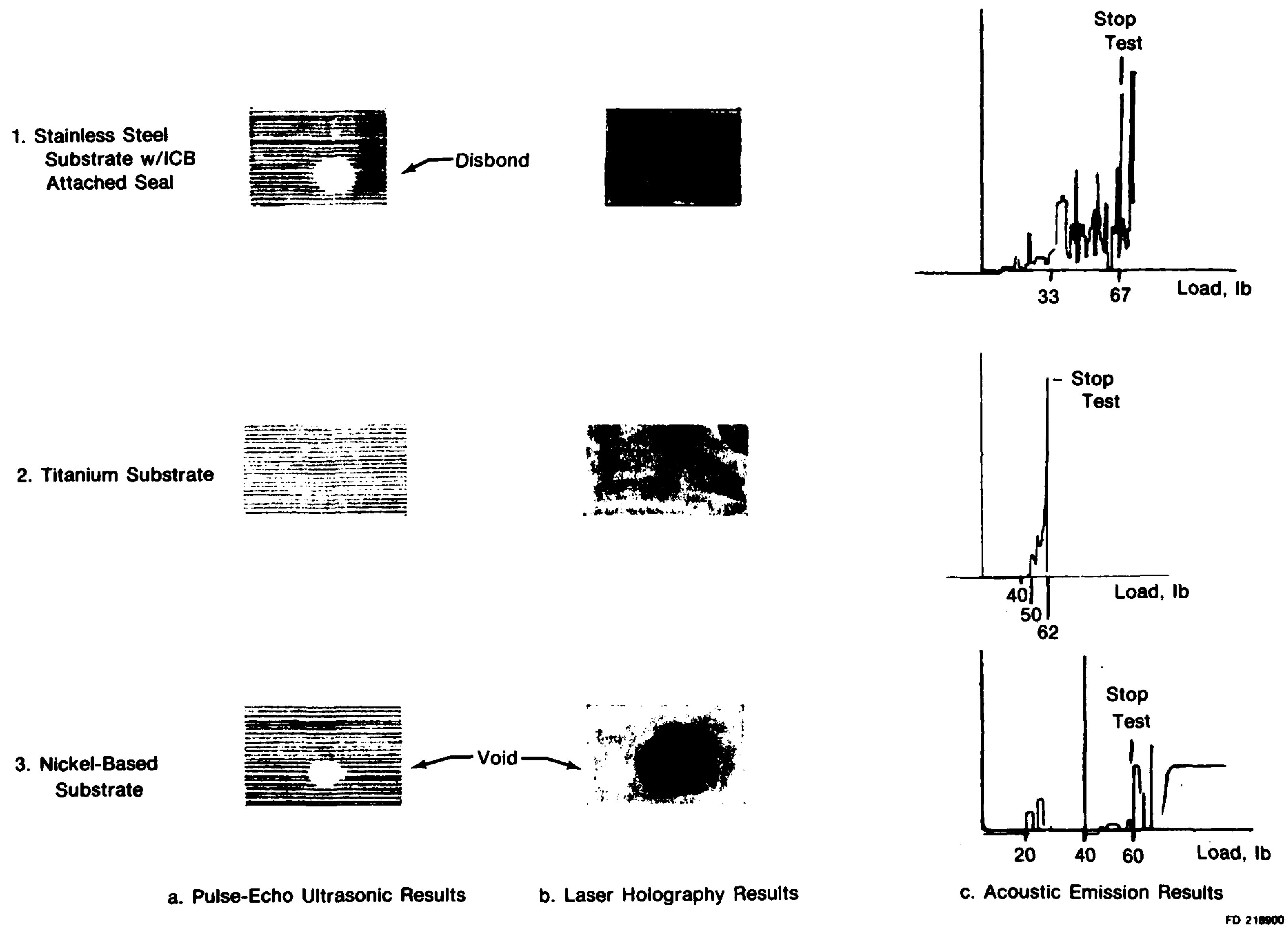
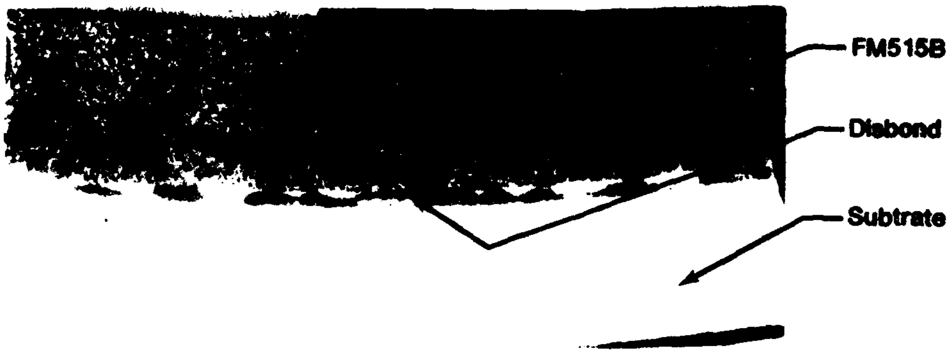


Figure 23. Ring Nondestructive Inspection Results

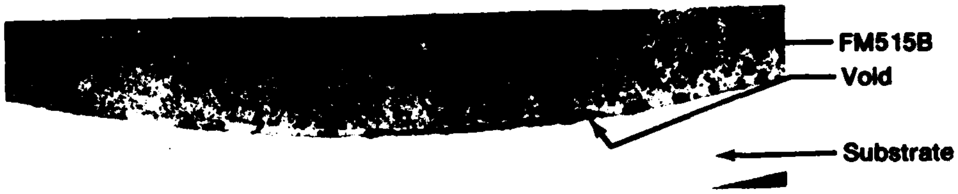


Mag: 10X a. Overall FAL 62683

Mag: 25X b. Close-Up FAL 62684

FD 210601

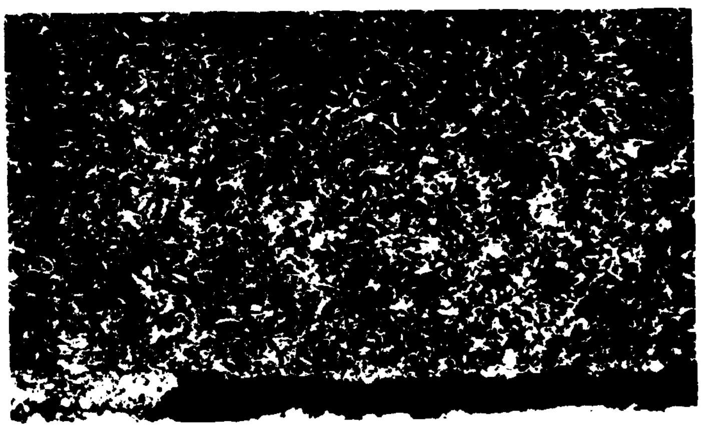
Figure 24. Disbond Defect Morphology



Mag: 12.5X

FAM 94193

a. Overall



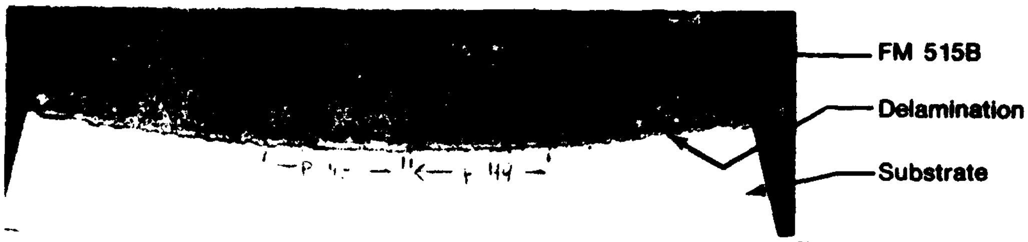
Mag: 25X

FAM 93841

b. Close-Up

FD 210603

Figure 25. ICB Void Morphology



Mag: 10X

a. Overall

Mag: 25X

b. Close-Up

FD 210602

Figure 26. Delamination Defect Morphology

Several conclusions regarding the capabilities of the two inspection techniques are apparent. Laser holography required defects larger than 0.30 in. to be detected. Also, laser holography was capable of distinguishing between delamination and disbond/void defects. However, neither pulse-echo ultrasonic nor laser holography was capable of distinguishing between disbonds or voids. Pulse-echo ultrasonic NDI identified disbond/void defects as small as 0.15 in. but could not detect delaminations. Defect sizes as determined by destructive metallography were within 15% of the size as indicated by both NDI techniques.

The results of acoustic emission testing ring samples is shown in Figure 23.c. These results were used to generate predicted ultimate tensile strengths using the technique previously described. The same samples were then destructively tested to determine their ultimate tensile strengths. A comparison of these data is shown in Figure 27 and indicated that predicted tensile strengths were within 5% of the tensile strengths as measured destructively. Reasonable agreement between the predicted and the destructively measured tensile strengths existed for both defect and defect free areas of ICB attachments.

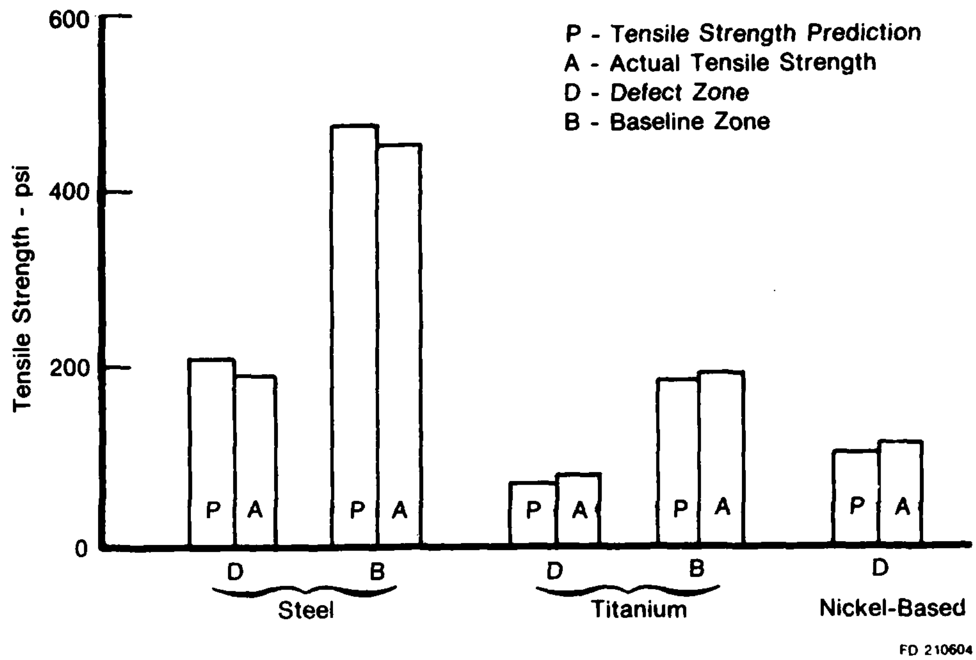


Figure 27. Acoustic Emission Tensile Strength Predictions

Task 3 — NDI Evaluations

FM 515B seal attachments, which were previously applied to engine hardware and a rub abradability rig shoe, were nondestructively inspected. The rig shoe seal attachment had previously been rub abradability tested.

Each of the three 120-deg segments that comprised the engine hardware inner seal land were inspected using pulse-echo and laser holography techniques. Nondestructive inspection scans of the engine hardware ICB attachments are shown in Figure 28.

Two indications of ICB defects were indicated by the pulse-echo NDI technique. However, close examination revealed that these indications matched perfectly with hardware raised plaforms as shown in Figure 29. Discounting these reflections, pulse-echo ultrasonic NDI indicated that ICB seal attachments were completely free of disbond/void defects. Laser holography NDI showed that two seal segments were completely free of ICB attachment defects. The third seal segment contained a delamination that comprised less than 1% of the engine hardware's total seal attachment area. The size of this defect is considerably less than the commonly employed P&WA reject limit for gas path seal attachments.

Acoustic emission NDI of the engine hardware seal attachment was also attempted, but lead time to procure transducers small enough to permit inspection of the engine hardware was not available. Since it is debatable whether or not the acoustic emission technique is truly nondestructive, and since reliable results can be obtained by the other two techniques, acoustic emission inspection was not pursued.

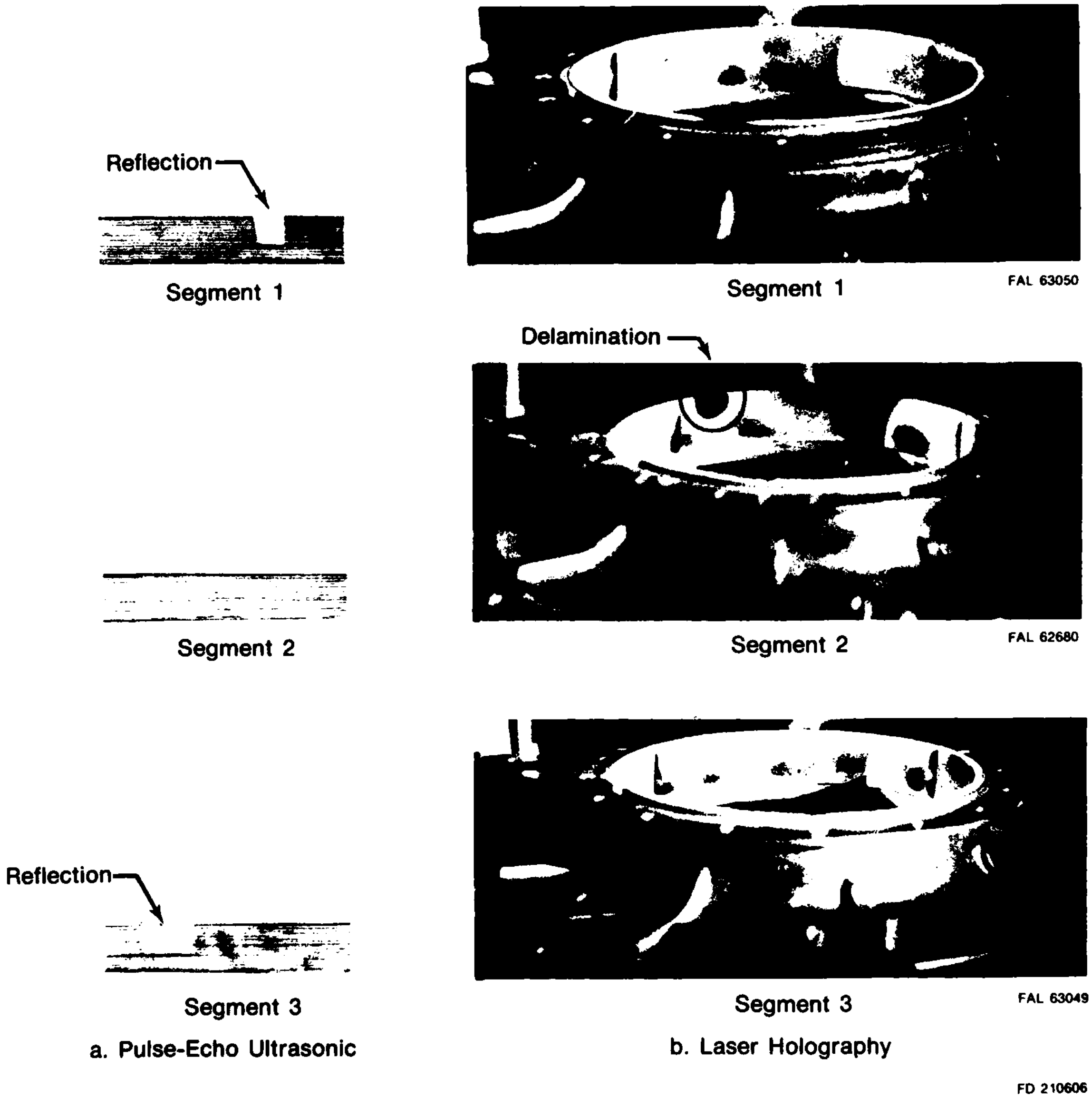


Figure 28. Diffuser Assembly NDI Analysis

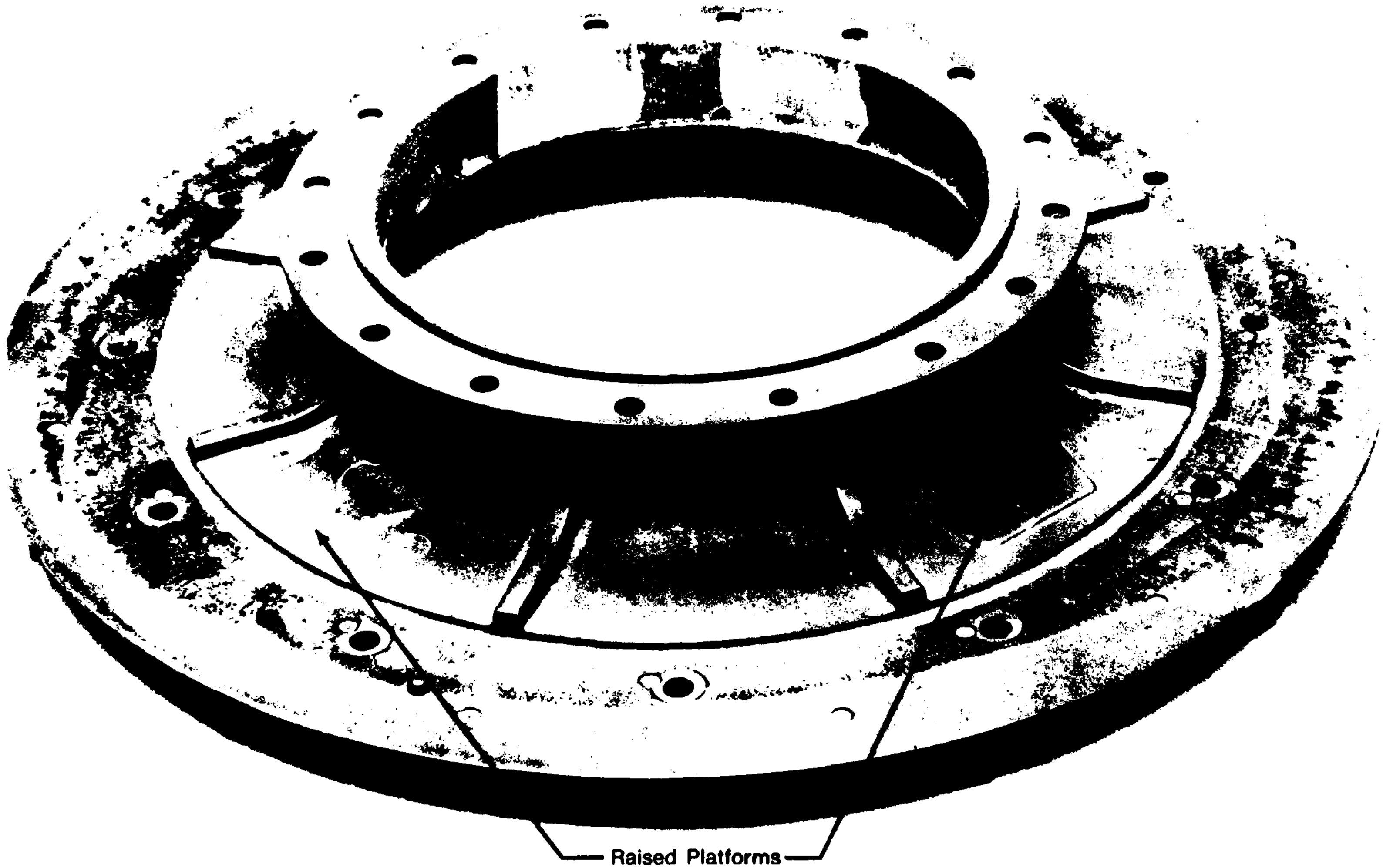
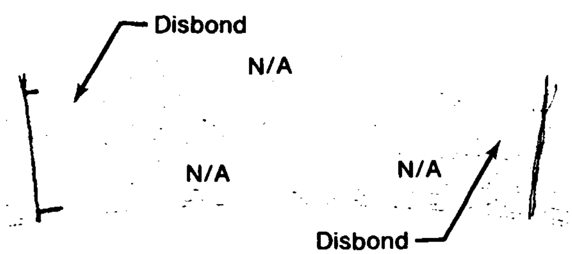
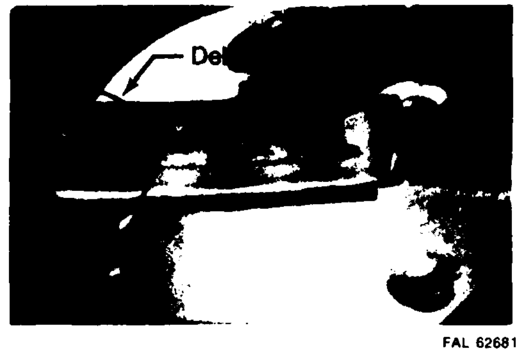


Figure 29. Army Hardware Geometry Responsible for Ultrasonic Defect Appearance

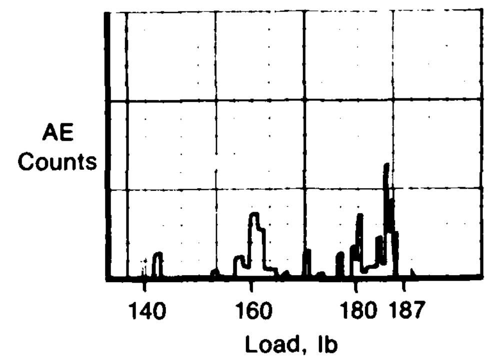
a. NDI



1. Pulse-Echo Ultrasonic

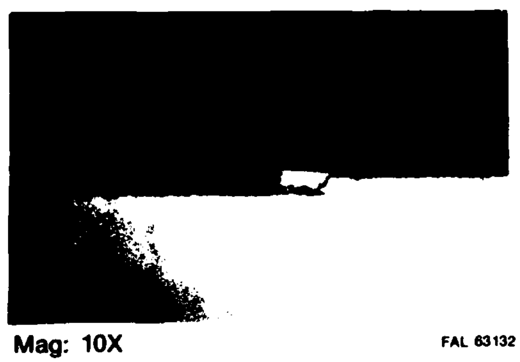


2. Laser Holography

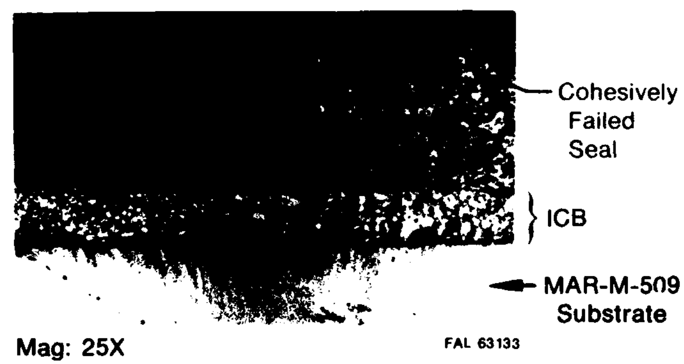


3. Acoustic Emission

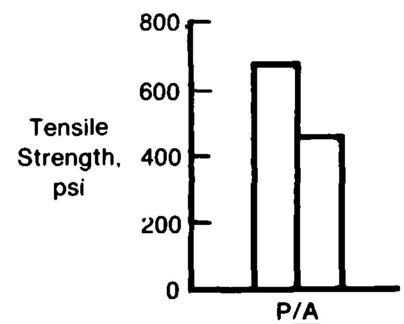
b. Destructive Analysis



1. Defect Zone



2. Rub Zone



3. Tensile Data

P - Tensile Strength Prediction
A - Actual Tensile Strength

FD 210605

Figure 30. Rub Shoe NDI and Destructive Analysis

The rub shoe which was selected for NDI had undergone a 0.020-in. incursion, the most severe rub tested. Figure 30 shows pulse-echo ultrasonic, laser holography and acoustic emission NDI results which are compared to post-NDI destructive analyses. Pulse-echo and laser holography techniques revealed small bond defect areas which were confirmed by destructive metallography. These defects were outside of the rub area and might have been present before the sample was rub rig tested. Unfortunately, NDI techniques were not established prior to rub rig testing; therefore, the integrity of the ICB seal attachments prior to rub rig testing could not be nondestructively determined.

Figure 30.a.1 shows three bond integrity suspect areas which were traced to thermocouple resistance weld zones on the backside of the rub shoe. The resistance welded areas produce spurious pulse-echo indications which were discounted.

A comparison of predicted tensile strength, as determined by acoustic emission NDI, and ultimate tensile strength, which was destructively measured, is shown in Figure 30.b.3. The relatively large discrepancy in tensile strengths is a consequence of inadequate contact between the transducer and a step in the abradable that was caused by the rub incursion.

The laser holography technique employed during Phase III is experimental, and requires the use of expensive equipment that is not readily available. Therefore, the use of the pulse-echo ultrasonic technique to nondestructively inspect ICB seal attachment is the preferred approach.

PHASE IV — ECONOMIC ANALYSIS

An economic analysis of the ICB seal attachment process was conducted. Materials, labor and tooling costs were included in the analysis. These costs were compared to the cost of gold-nickel (Au-Ni) braze attachment of abradable seals, since this is an established abradable seal attachment scheme.

The cost analysis involved estimates for the attachment of FM 515B seals to 1000 Allison T-63 Front Diffuser Assembly seal lands. The cost comparison for both seal attachment techniques is shown in Table 6.

TABLE 6. SEAL ATTACHMENT COST COMPARISON

	ICB		*Au-Ni Braze*	
	Cost, $	*Au-Ni Total, %*	*Cost, $*	*Au-Ni Total, %*
Material	21	2.5	148	17.7
Labor				
● Manufacturing	210	25.0	416	49.6
● Inspection	210	25.0	210	25.0
● Engineering Support	9	1.0	9	1.0
Tooling				
● Materials	3	0.4	42	5.1
● Labor	26	3.1	13	1.5
Total	479	57.0	839	100.0

ICB attachment material costs included the cost of ICB, FM 515B and Metco 405 NiAl undercoat. These costs were based on expenses incurred during this program. Material costs for Au-Ni braze attachment included the cost of Au plating, Ni flashing and FM 515B seals.

Labor costs for both attachment techniques included manufacturing, inspection and engineering support labor. Costs for ICB attachments were estimated based on experience gained during this program. Labor costs for Au-Ni braze attachments were based on P&WA manufacturing experience. Cost estimates included the labor required to inspect seal attachments using all three NDI techniques which were investigated under this program. Practical inspection would involve the use of only one NDI technique. This would decrease the total cost equally for attaching seals by both methods.

Estimates included material and labor required to fabricate tooling for each of the attachment schemes. A labor rate of $35/hr was assumed in the comparison.

Table 6 shows that ICB seal attachment provides a potential cost-saving of 43% compared to Au-Ni braze attachment. The cost-saving is a consequence of lower material and tooling costs and reduced manufacturing labor cost. This cost-saving is achievable without a tradeoff in quality based on evaluations of the ICB seal attachments conducted under this program. These evaluations indicate that ICB will survive turbine engine gas path seal environments up to 1000°F.

Cost estimates for equipment used during the ICB bonding operation are listed in Table 7. Most of the equipment is already available at engine manufacturers and overhaul centers. Therefore, additional capital equipment would not have to be procured to incorporate the ICB attachment scheme.

TABLE 7. ESTIMATED EQUIPMENT COSTS

Equipment	*Estimated Cost, $*
Humidity and Temperature Room Control System	10,000
Band Saw	1,000
Spray Booth	30,000
Oven	1,000
Furnace	8,000
Automatic Controller	5,000
Grit, Blast System	5,000
Laser Holography Set-Up	100,000
Ultrasonic Set-Up	35,000
Acoustic Emission Set-Up	50,000

SECTION III

CONCLUSIONS

Inhibited Chem-Braze (ICB) manufacturing methods for attaching FELTMETAL® abradable seals to gas turbine engine compressor blade tip shrouds were established. The manufacturing methods were successfully employed to attach abradable seals to steel, titanium and nickel-base alloys. The integrity of the ICB attachment was verified by second bending mode vibration and rub abradability rig tests.

Tooling, which is used during the ICB bonding operation, was designed and fabricated. It consisted of a doctor blade for the controlled deposition of ICB slurry and expandable ring segments to apply bonding pressure. The use of these tools was successfully demonstrated in the ICB attachment of an abradable seal to an Army supplied Allison T-63 front diffuser assembly.

A quick and inexpensive chemical stripping technique developed under a previous contract was optimized for removing worn abradable seals. The technique involves the immersion of engine hardware with ICB attached seals in concentrated aqueous sodium hydroxide at 160 to 180°F for 2 to 3 hr.

A number of NDI techniques for evaluating the integrity of ICB bond attachments were investigated. A recently developed laser halography technique can identify all possible types of ICB bond defects. However, engine manufacturers and overhaul centers might not have access to this sophisticated NDI equipment; therefore, a more practical pulse-echo ultrasonic NDI technique was selected as the preferred approach.

An economic analysis indicated a 43% cost-savings for attaching abradable seals with ICB compared to gold-nickel braze attachment. These savings are a consequence of reduced material, labor and tooling costs.

The use of the established manufacturing methods for ICB bonding abradable seals to selected magnesium and aluminum alloys was not successful. However, alternate alloys or modified ICB bonding techniques which offer potential for sucessful seal attachment were identified.

SECTION IV

RECOMMENDATIONS

The standard ICB technique for attaching FELTMETAL® abradable seals resulted in partial annealing of high strength aluminum and magnesium alloys. A modified procedure was attempted to retain the high strength of aluminum substrates while attaching FELTMETAL seals. The modified procedure included subjecting ICB attached seals to a rapid water quench which distorted the metal substrate; however, it did not cause bond detachment.

It is recommended that other heat treatment quench mediums for use in conjunction with aluminum substrates, be investigated. In addition, mechanical fixturing may also be necessary to restore aluminum substrates to their original configuration after heat treat quenching.

It is also recommended that any of the commercially-available, thermally-hardenable magnesium alloys identified in this program be investigated for ICB seal attachment.

APPENDIX A

ICB CEMENT FORMULATION

GENERAL DESCRIPTION

Inhibited Chem-Braze (ICB) cement is formulated by combining 10 wt% of reagent grade glycerin to a premixed solution of Sermabond 481 high temperature cement. Specifications for both the Sermabond 481 cement and Glycerin are as follows:

Sermabond 481 is an inorganic ceramic metallic compound that matures to an insoluble, machinable, tenaciously bonded cement. The coating is a two-part mix which consists of aluminum powder in a chromium modified alkali silicate binder and zinc oxide powder.

SOURCE

Sermetal Incorporated, Limerick, Pennsylvania

PREPARATION OF CEMENT

Sermabond 481 is shipped in a two-part mix and has a six-month shelf life. When the powders are mixed with the liquid, the shelf life is limited to 2 weeks. The contents of the two containers should be thoroughly mixed by mechanically stirring at a rate adjusted to keep trapped air to a minimum, (entrapped air causes voids in the cured compound). The mixed material should be allowed to stand 18 to 20 hours before using; this allows time for the reaction of the activator to take place. At this point 10 wt% glycerin shall be added to the cement. If less than the total contents are to be mixed, the following quantities should be used:

To 100 ml of Part I by volume add 4.35 gm of Part II

To 100 gm of Part I by weight add 2.35 gm of Part II

CEMENT PRODUCT DATA

481-2 Part I

Weight Per Gallon	14.5 lb min
Viscosity	Paste
Principal Pigment	Aluminum
Solids	70% min
Color	Grey

481-2 Part II

Color	White
Specific Gravity	5.6
Structure	Crystalline Powder

TOXICITY

Although Sermabond 481 is of low toxicity, care should be taken to avoid ingestion. Skin contact may produce irritation. In case of skin contact, immediately rinse with running water.

GLYCERIN SPECIFICATION

Reagent Grade Glycerin	99.5 vol %
Residuals After Ignition	0.005
Chlorinated Compounds	0.003
Sulfate	0.001
Fatty Acid Esters	0.05
Heavy Metals; e.g., Pb	2 ppm

APPENDIX B

FELTMETAL® ABRADABLE SEALS

FELTMETAL® FM 515B was used throughout this program except during rub rig testing. FELTMETAL 1109 was used during the rub rig tests. Both of these commercially available abradable seal materials are defined in Tables B-1 through B-4.

Source: Brunswick Corporation, Technetics Division, Deland, Florida

Hastelloy X FELTMETAL (FM 515B)

Tables B-1 and B-2 show typical mechanical properties and fiber alloy composition for FM 515B FELTMETAL.

Table B-1. Typical Mechanical Properties

*Product Tensile** No.*	*Alloy*	*Density*	*Compressive Modulus**	*Compressive Strength** at 5% Strain*	*Tensile Modulus**	*Ultimate Strength*
FM 515B	Hastelloy X	19.0	1.3 (0.9)	330 (227)	2.9 (2.0)	1400 (965)

*Modulus values are in psi × 10^4 — numbers in () are in N/m^2 × 10^8
**Strength values are in psi — numbers in () are in N/m^2 × 10

Table B-2. Fiber Alloy Composition

Alloy	*Ni*	*Co*	*Cr*	*Mo*	*W*	*Fe*	*C*	*Si*	*Mn*
Hastelloy X*	Bal	1.5	22	9	0.6	18	1.10	1.0 max	1.0 max

*Trademark of Cabot Corporation

Stainless Steel FELTMETAL (FM 1109)

Tables B-3 and B-4 show typical physical properties and fiber alloy composition for FM 1109 FELTMETAL.

Table B-3. Typical Physical Properties

Product Number	*Fiber*	*Density %*	*Thickness in.*	*Area Density (lb/ft²)*	*Median Pore Size μ*	*Pore Size Range μ*	*Tensile Strength (psi)*	*Surface Area (cm²/GM)*	*Surface Area (in²/lb)*	*Thermal Conductivity Btu-ft/hr-ft²°F*	*Electrical Resistivity (μcm)*	*Flow Resistance (CGS Rayls)*
FM 1109	A-8	40	0.125	2.08	13.5	7-27	6,000	560	39,000	0.24	700	3,100

Table B-4. Fiber Alloy Composition

Alloy	*Fe*	*P*	*Cr*	*S*	*Ni*	*C*	*Si*	*Mn*	*Cb*	*Ta*
347 SS	Bal —	0.045 Max	17.00 19.00	0.030 Max	9.00 13.00	0.08 Max	1.00 Max	2.00 Max	0.50 Max	0.50 Max

APPENDIX C

ICB ATTACHMENT PROCEDURE

1. Mix Sermabond 481 and add 10 wt% glycerin
2. Flamespray 0.003 to 0.005 in. thick* Metco 405 undercoat to substrate
3. Cut radiused FM into segments for a 360 deg seal
4. Apply 0.008 to 0.012 in. thick ICB cement to undercoated substrate
5. Apply ICB cement to mating FELTMETAL® surfaces and remove excess
6. Mate seal to substrate and apply 200 psi radial load
7. Dry assembly at 60 to 65°F for 12 hr minimum
8. Place in oven and dry at 175°F for 1 hr
9. Increase temperature at 1°F/minute to 200°F and hold for 1 hr
10. Release load
11. Increase temperature from 200 to 450°F at 5°F/min and hold at temperature for 1 hr
12. Increase temperature to 750°F** at 10°F/min and cure for 1 hr
13. Increase temperature to 1000°F at 10°F/min and hold at temperature for 1 hr
14. Allow slow furnace cool to less than 500°F (approximately 3 to 4 hr)

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*Metallographic examination showed that 100% substrate coverage required 0.003 to 0.005 in. coating thickness.

**750°F intermediate cure stage is preferred over 700°F listed in AVRADCOM TR80-F-5 for improved bonding.

APPENDIX D

AMS SPECIFICATIONS

Condensed AMS specifications for alloys employed in this program are presented below. The complete details for all specifications are available from the Society of Automotive Engineers, Inc.

AMS 4115 ANNEALED ALUMINUM ALLOY BARS AND RINGS

SCOPE

Form: This specification covers an aluminum-base alloy in the form of rolled, drawn, or cold finished bars, rods, and wire, flash welded rings, and stock for flash welded rings.

Application: Primarily for parts requiring moderate strength, especially where such parts and assemblies require brazing or welding during fabrication.

Composition: Shall conform to the following wt%, determined in accordance with AMS 2355:

	Min	*Max*
Magnesium	0.8	1.2
Silicon	0.40	0.8
Copper	0.15	0.40
Chromium	0.04	0.35
Iron	—	0.7
Zinc	—	0.25
Manganese	—	0.15
Titanium	—	0.15
Other Impurities, each	—	0.15
Other Impurities, total	—	0.15
Aluminum	remainder	

AMS 4117 ALUMINUM ALLOY BARS AND RINGS

SCOPE

Form: This specification covers an aluminum-based alloy in the form of rolled, drawn, or cold finished bars, rods, and wire, flash welded rings, and stock for flash welded rings.

Application: Primarily for parts requiring moderate strength where limited formability is acceptable.

TECHNICAL REQUIREMENTS

Composition: Shall conform to the following wt%, determined in accordance with AMS 2355:

	Min	*Max*
Magnesium	0.8	1.2
Silicon	0.40	0.8
Copper	0.15	0.40
Chromium	0.04	0.35
Iron	—	0.7
Zinc	—	0.25

Manganese	—	0.15
Titanium	—	0.15
Other Impurities, each	—	0.05
Other Impurities, total	—	0.15
Aluminum	remainder	

Condition: The product shall be supplied in the following condition:

Bars, Rods, and Wire: Rolled, drawn, or cold finished, as ordered, and solution and precipitation heat treated.

Flash Welded Rings: Solution and precipitation heat treated.

AMS 4025 ALUMINUM ALLOY SHEET AND PLATE

SCOPE

Form: This specification covers an aluminum-base alloy in the form of sheet and plate.

Application: Primarily for parts where moderate formability and response to heat treatment are required.

Military Specifications

MIL-H-6088 — Heat Treatment of Aluminum Alloys

TECHNICAL REQUIREMENTS:

Composition: Shall conform to the following wt%, determined in accordance with AMS 2355:

	Min	*Max*
Magnesium	0.8	1.2
Silicon	0.40	0.8
Copper	0.15	0.40
Chromium	0.04	0.35
Iron	—	0.7
Zinc	—	0.25
Manganese	—	0.15
Titanium	—	0.15
Other Impurities, each	—	0.05
Other Impurities, total	—	0.15
Aluminum	remainder	

Condition: Annealed in accordance with MIL-H-6088.

AMS 4375 MAGNESIUM ALLOY SHEET AND PLATE

SCOPE

Form: This specification covers a magnesium alloy in the form of sheet and plate.

Application: Primarily for low-strength parts requiring rigidity with low density.

Military Specifications

MIL-STD-649 — Aluminum and Magnesium Products, Preparation for Shipment and Storage.

TECHNICAL REQUIREMENTS:

Composition: Shall conform to the following wt%, determined in accordance with AMS 2355:

	Min	Max
Aluminum	2.5	3.5
Zinc	0.7	1.3
Manganese	0.20	—
Silicon	—	0.05
Copper	—	0.05
Calcium	—	0.04
Iron	—	0.005
Nickel	—	0.005
Other Impurities, total	—	0.30
Magnesium	remainder	

Condition:

Product 0.500 in. (12.70 mm) and Under in Nominal Thickness: Annealed, recrystallized, and pickled.

Product Over 0.500 in. (12.70 mm) in Nominal Thickness: Annealed and recrystallized.

AMS 4911 TITANIUM ALLOY SHEET STRIP AND PLATE ANNEALED

SCOPE

Form: This specification covers a maganesium alloy in the form of sheet strip and plate.

Application: Primarily for parts requiring strength up to 750°F (400°C). Certain processing procedures and service conditions may cause this material to be subject to stress-corrosion cracking; ARP 982 recommends practices to minimize such conditions.

TECHNICAL REQUIREMENTS

Composition: Shall conform to the following percentages by weight, determined by wet chemical methods in accordance with ASTM E120, by spectrographic methods in accordance with Federal Test Method Standard No. 151, Method 112, or by other approved analytical methods:

	Min	*Max*
Aluminum	5.50	6.75
Vanadium	3.50	4.50
Iron	—	0.030
Oxygen	—	0.20
Carbon	—	0.08
Nitrogen	—	0.05 (500 ppm)
Hydrogen	—	0.015 (150 ppm)
Yttrium	—	0.005 (50 ppm)
Residual Elements, each (3.1.1)	—	0.10
Residual Elements, total (3.1.1)	—	0.40
Titanium	remainder	

Annealing: The product shall be annealed by heatıng to a temperature within the range 1300 to 1650°F (705 to 900°C), holding at the selected temperature within ±25°F (±15°C) for a time commensurate with the thickness and the heating equipment and procedure used, and cooling at a rate which will produce product meeting the requirements.

AMS 4928G TITANIUM ALLOY BARS AND FORGINGS

SCOPE

Form: This specification covers a titanium alloy in the form of bars, wire, forgings, flash welded rings, and stock or flash welded rings.

Application: Primarily for parts requiring strength up to 750°F (399°C) where response to heat treatment is not required.

TECHNICAL REQUIREMENTS

Composition: Shall conform to the following wt%, determined by wet chemical methods in accordance with ASTM E120, by spectrographic methods in accordance with Federal Test Method Standard No. 151, Method 112, or by other approved analytical methods:

	Min	Max	
Aluminum	5.50	6.75	
Vanadium	3.50	4.50	
Iron	—	0.030	
Oxygen	—	0.20	
Carbon	—	0.10	
Nitrogen	—	0.05	(500 ppm)
Hydrogen	—	0.0125	(125 ppm)
Other Elements, total (3.1.2)	—	0.40	
Titanium	remainder		

Annealing: Bars, wire, forgings, and flash welded rings shall be annealed by heating to a temperature within the range 1300 to 1450°F (704.4 to 787.8°C), holding at the selected temperature within ±25°F (±14°C) for not less than 1 hr, and cooling at a rate which will produce products meeting all requirements of this specification and capable of meeting the requirements after heating to any temperature up to 1200°F (649°C), holder at heat for 20 min, cooling in air, and descaling.

AMS 5398 STEEL CASTINGS, SAND AND CENTRIFUGAL, CORROSION RESISTANT

SCOPE

Form: This specification covers a corrosion-resistant steel in the form of sand or centrifugal castings.

Application: Primarily for parts such as accessory components requiring corrosion resistance and strength up to 600°F (315°C). Certain processing procedures and service conditions may cause this steel to be subject to stress-corrosion cracking. Where stress-corrosion may be a factor in service, precipitation heat treatment should be performed at a temperature not lower than 1000°F (540°C).

TECHNICAL REQUIREMENTS

Composition: Shall conform to the following percentages by weight, determined by wet chemical methods in accordance with ASTM E353, by spectrographic methods in accordance with Federal Test Method Standard No. 151, Method 112, or by other approved analytical methods:

	Min	Max
Carbon	—	0.06
Manganese	—	0.70
Silicon	0.50	1.00
Phosphorus	—	0.04
Sulfur	—	0.03
Chromium	15.50	16.70
Nickel	3.60	4.60
Columbium + Tantalum	0.10	0.35
Copper	2.50	3.20
Nitrogen	—	0.05

Condition: Solution heat treated.

Casting: A melt shall be the metal poured from a single furnace charge of 15,000 lb (6810 kg) or less.

AMS 5504
STEEL SHEET, STRIP, AND PLATE, CORROSION AND MODERATE HEAT RESISTANT

SCOPE

Application: Primarily for parts and assemblies requiring oxidation resistance up to 1000°F (538°C), but useful at the higher temperatures only when stresses are low.

Composition:

	Min	*Max*
Carbon	—	0.15
Magnesium	—	1.00
Silicon	—	1.00
Phosphorus	—	0.040
Sulfur	—	0.030
Chromium	11.50	13.50
Nickel	—	0.75
Molybdenum	—	0.50
Aluminum	—	0.05
Nitrogen	—	0.08
Copper	—	0.05
Tin	—	0.05

AMS 5536G
ALLOY SHEET AND PLATE, CORROSION AND HEAT RESISTANT

SCOPE

Application: Primarily for parts such as welded nozzle diaphragm assemblies, burner liner parts, tailpipes, exhaust cone assemblies, and other parts requiring oxidation resistance up to 220°F (1204°C) and relatively high strength above 1500°F (815°C).

Composition:

	Min	*Max*
Carbon	0.05	0.15
Magnesium	—	1.00
Silicon	—	1.00
Phosphorus	—	0.040
Sulfur	—	0.030
Chromium	20.50	23.00
Cobalt	0.50	2.50
Molybdenum	8.00	10.00
Tungsten	0.20	1.00
Boron	Present but not exceeding	0.010
Iron	17.00	20.00
Nickel	Remainder	

Sheet and Strip: Hot or cold rolled, solution heat treated, and descaled unless solution heat treatment is performed in an atmosphere yielding a bright finish, having a surface appearance as close as possible to a commercial corrosion resistant steel No 2D finish; standards for acceptance and rejection shall be as agreed upon by purchaser and vendor.

Plate: Hot rolled, solution heat treated, and descaled.

SCOPE

Application: Primarily as an investment-cast vane alloy to operate at temperatures around 1800°F.

Composition:

	Cr	Ni	W	Ta	C	Ti	Zr[a]	Mn	Si	B	Fe	S	Co
Maximum	24	19	7.5	4	0.65	0.25	0.60						
Minimum	21	9	6.5	3	0.55	0.15	0.40	0.10	0.40	0.01	1.50	0.015	Balance

Alloy lots containing lower zirconium content (0.3 to 0.1%) are commonly supplied to avoid interaction problems.

TECHNICAL REQUIREMENTS

Heat Treatment: Alloy is commonly used as-cast. However, a solution treatment of 2300°F for 4 hr improves tensile strength and ductility.

APPENDIX E

TENSILE STRENGTH SAMPLE PREPARATION AND TEST PROCEDURE

SAMPLE PREPARATION

Tensile strength test samples were prepared by applying ICB and FM515B abradable seals to bond bars as shown in figure E-1. The bond bar assemblies were then cured as described in the text. Scotchweld EC2186 epoxy adhesive was used to attach mating bond bars. Some assemblies were tested without FM515B present. These were assembled the same as shown in figure E-1 except no abradable was used.

TENSILE STRENGTH TESTING

Assembled and cured bond bars were tensile tested in a Tinius Olsen Testing Machine at a strain rate determined by crosshead speed maintained at 0.050 ± 0.002 in./in./min.

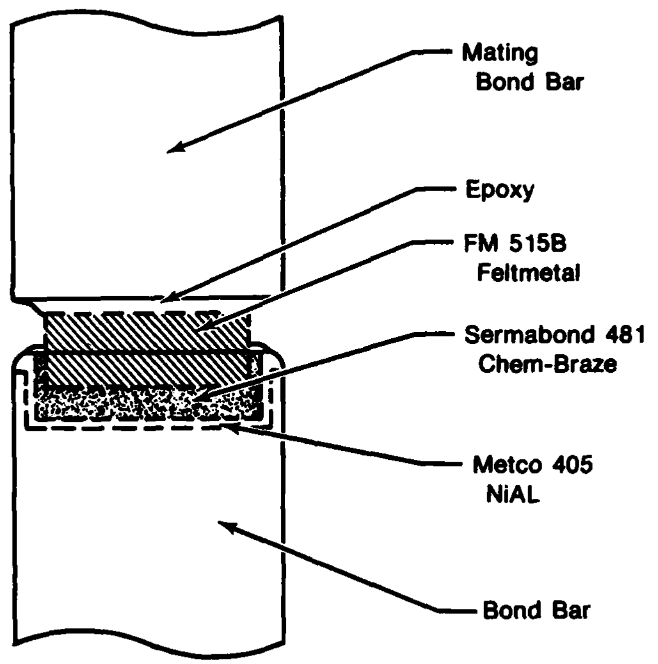

Figure E-1. Seal Attachment Tensile Test Assembly Schematic

APPENDIX F

RIG TEST SAMPLE PREPARATION AND TESTING PROCEDURES

SECOND BENDING MODE VIBRATION TESTING

Samples were prepared by ICB bonding FM515B FELTMETAL® to steel, titanium and nickel-based plates as shown in figure F-1.

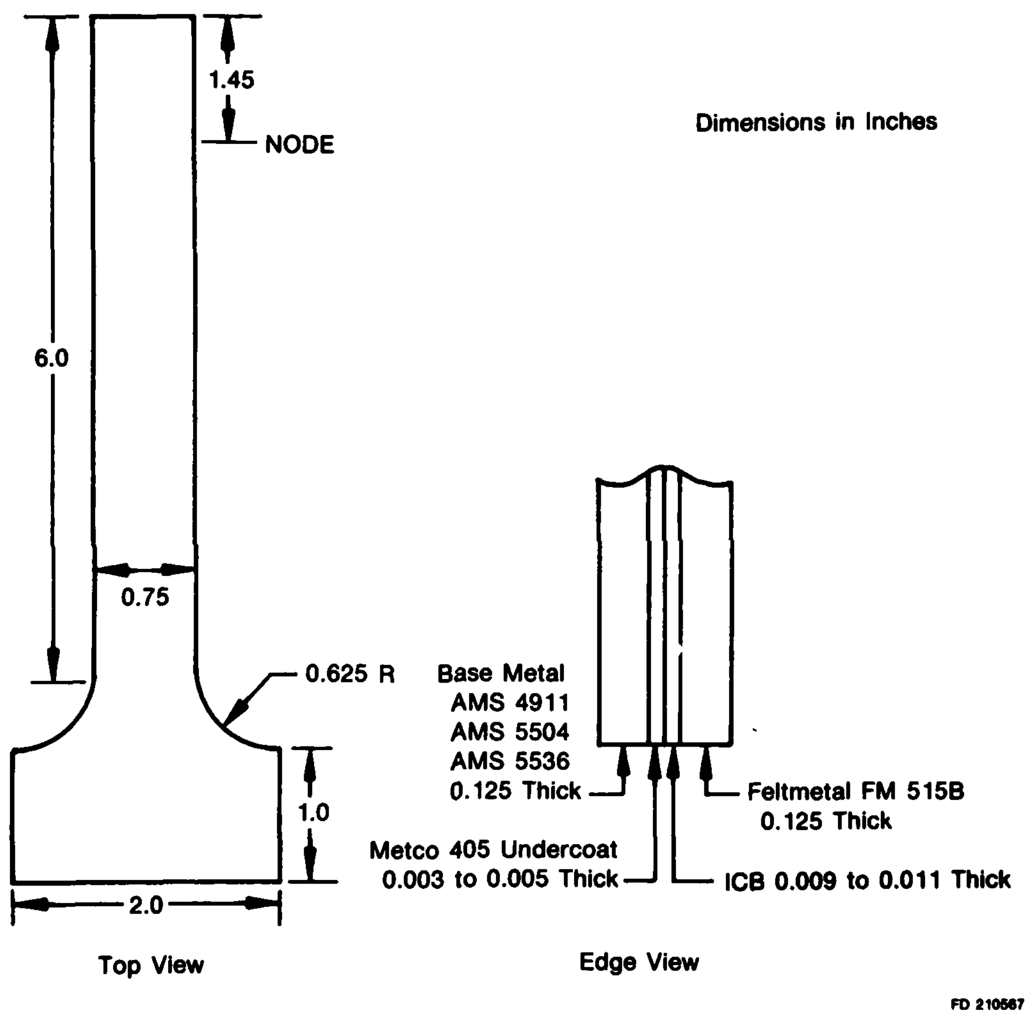

Figure F-1. Vibration Test Sample

The specimens were clamped at a point approximately 0.100 in. from the radiused sides at the large tab end forming a cantilever beam. The specimens were attached to a Ling Electronics, Inc. Model 390 Shaker, which is an air-cooled electrodynamic shaker designed to produce 3000 lb force vector over a frequency range of 5 to 3000 Hz. Electromagnetic current fluctuations through this instrument generate a vibration that extends into the test piece but is isolated from the instrument base and nearby surroundings. Strain values shown in the test data were based on measured deflections in each test piece at the point of maximum stress. Calibration test pieces were stress coated and tested to locate the maximum stress point for each alloy. Strain gages were used to identify the strain values obtained at that point. Since the strain gages could not withstand second bending mode vibration loads for extended periods of time, the calibration test piece deflection was measured and each strain value identified. Comparable deflection measurements were made on the actual test pieces to ensure data reproducibility.

The vibration tests were conducted at room temperature. Second bending mode vibration frequency for the various alloy substrates was calculated using the following equation.

$$f_{2\text{nd Bending}} = \frac{3}{4L} \sqrt{\frac{E}{\rho}} ,$$

where

L = test specimen length (in.)
E = tension — compression modulus of elasticity (psi)
ρ = density (lb/in.^{3})

Adjustments to the vibration frequency were made to obtain second bending vibration, because the test pieces were laminated structures whose overall system modulus of elasticity varied from that of just the metal substrate modulus used in the calculation.

DYNAMIC RUB RIG TESTING

Samples were prepared by ICB bonding FM1109 seals to the inner diameter of cast Mar-M509 rub shoes which are shown in figure F-2.

The rub shoes with ICB attached seals were rigidly clamped to a stationary fixture in the rub rig. A single AMS 4915 (Ti8-1-1) rub rig blade was attached to a disk which was rotated with an angular velocity of 13,300 rpm (340 ft/sec blade tip speed). Blade tip-seals were interacted at 0.0002 in./sec with interaction depths ranging from 0.005 to 0.020 in. The abradable surface temperature was maintained at 500°F while the back side of the rub shoe ranged from 900 to 950°F. Rub zones 0.08 in. wide by 0.003 to 0.015 in. deep were formed during incursions.

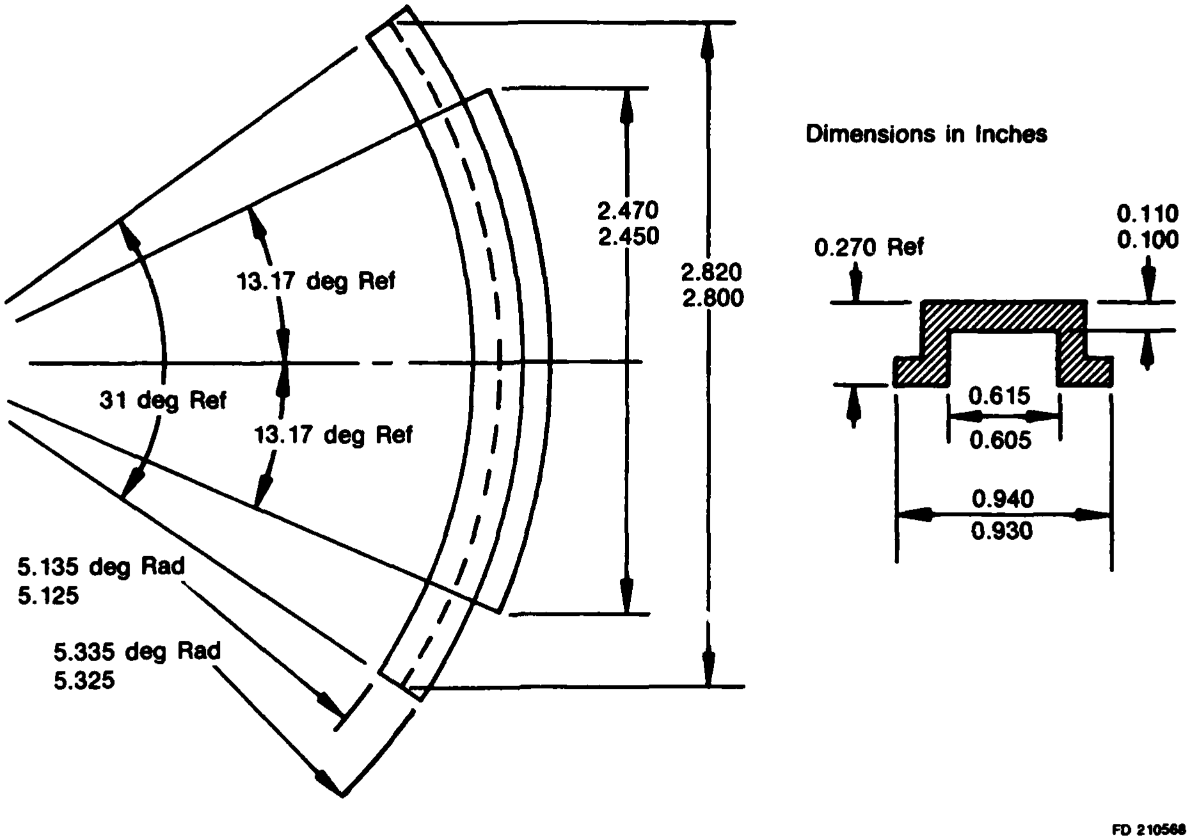

Figure F-2. Rub Shoe Schematic

APPENDIX G

EXPANDABLE RING SEGMENT TOOLS

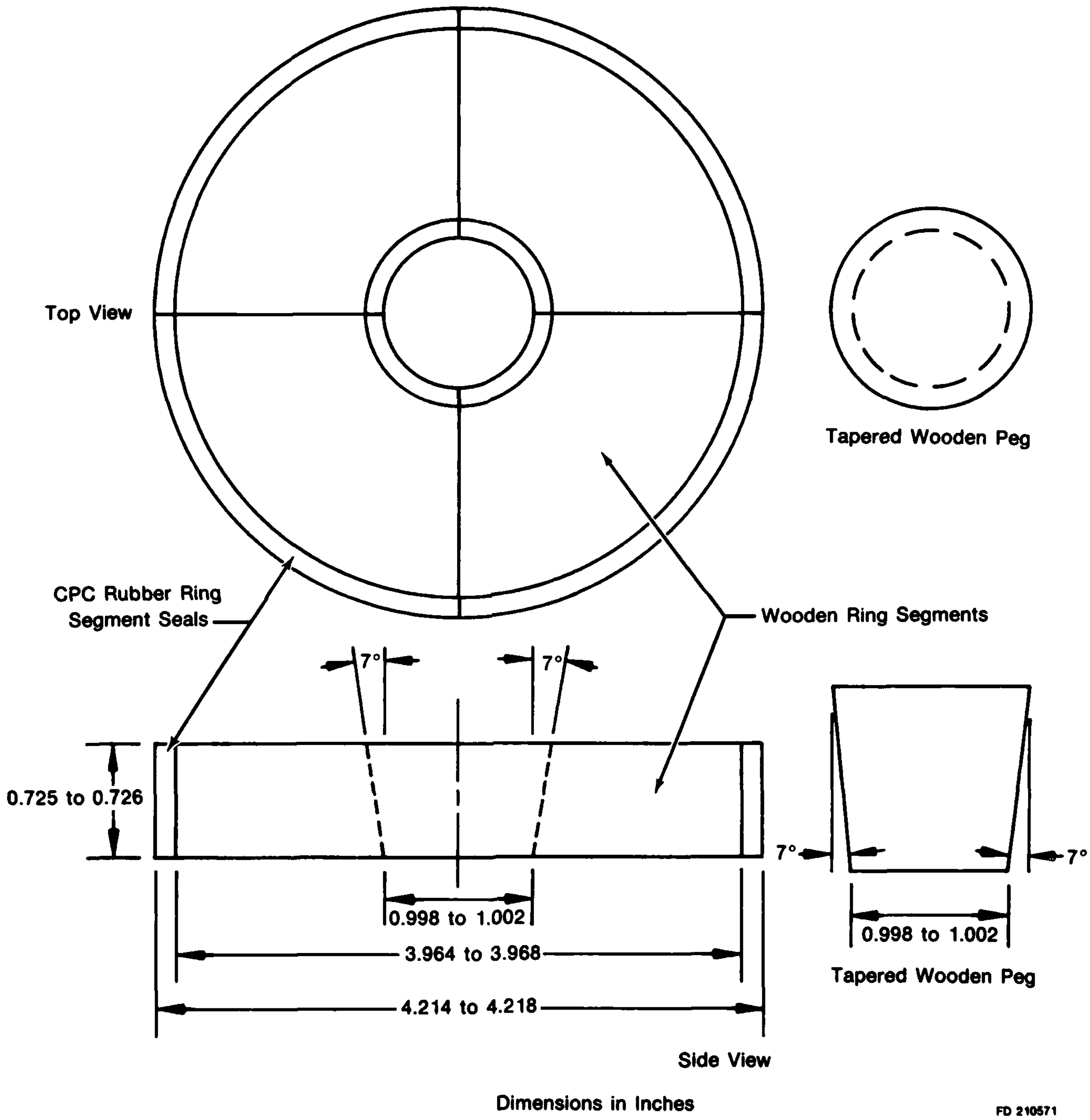

Figure G-1. Engine Hardware Expandable Ring Segment Design

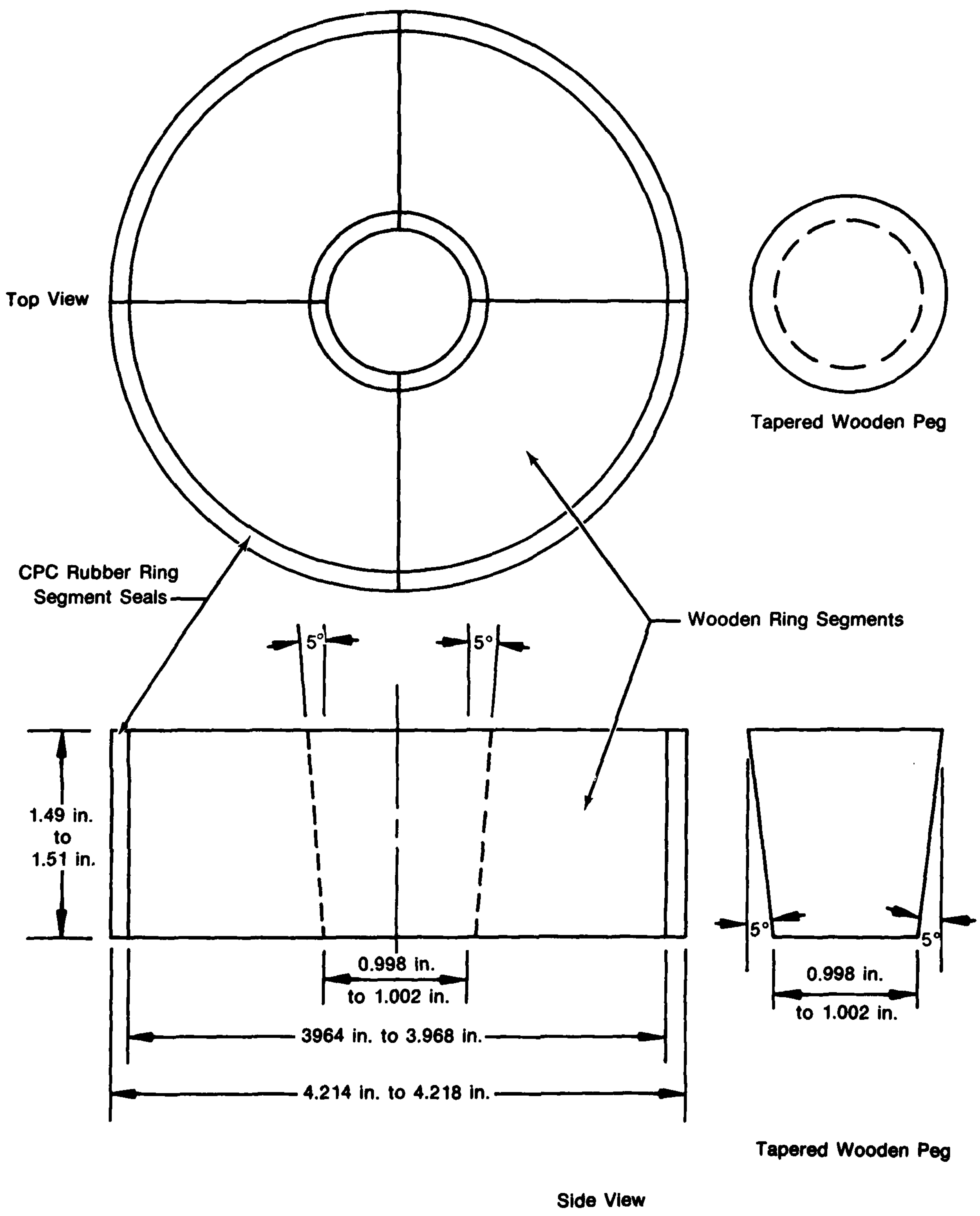

Figure G-2. Ring Geometry Expandable Ring Segment Design

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